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THE PROPORTIONAL COUNTER SOURCE FOR THE LOW ENERGY
CALIBRATION OF THE SUDBURY NEUTRINO OBSERVATORY

by

Ferenc J. R. Dalnoki-Veress

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

School of Physics,
Carleton University

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The undersigned hereby recommend to
the Faculty of Graduate Studies and Research
acceptance of the thesis

**The Proportional Counter Source for the Low Energy Calibration
of Sudbury Neutrino Observatory**

Submitted by

Ferenc Dalnoki-Veress, B.Sc., M.Sc.

in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

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Abstract

It is imperative that if a clean measurement is to be made of the Charged Current (CC) to Neutral Current (NC) ratio and the CC spectral distortion in the Sudbury Neutrino Observatory, the low energy background must be very well understood. For this reason a technique has been developed, so that each isotope of the background in the D₂O can be measured. The technique relies on a proportional counter (PCS), which acts both as a detector as well as a source. If various sources such as ^{228}Th are placed on the anode of the proportional counter, the beta-decay is tagged by the PCS and the Čerenkov radiation that is produced is detected by SNO. The method aims to make a background and distortion free measurement of the SNO detector response to a ^{228}Th source. This thesis discusses the construction, development, testing, quality control and assurance, deployment and analysis of the PCS.

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Finally, I would like to thank my beautiful wife Heekyeong. She has made my life complete, and her patience, love and encouragement seem to make everything possible!

희경씨. 사랑해요!

This thesis is dedicated to the 3 generations of women in my life: Omoesje, Mama, Amanim and Heekyeong

Acronym	Meaning
ADC	Analog-to-Digital converter
AV	Acrylic Vessel
CC	Charged Current Reaction
CMA	Controls Monitors and Alarms
ES	Elastic Scattering Reaction
DAQ	Data Acquisition
DCR	Deck Clean Room
EGS4	Electron Gamma Shower Code
ESC	Electrostatic Counters
EXT4	External trigger used for PCS in engineering run
FEC	Front End Card
FS	PCS Filling System
GT	Global Trigger
GTID	Global Trigger Identification Number
HEPDB	CERN database manager
HV	High Voltage
LEB	Low Energy Background
MANIM	Monitor and Alarms Module
MDG	Monitor Degasser used to assay Rn
MINUIT	CERNlib Function Minimization Software
NC	Neutral Current Reaction
NHIT100	SNO main neutrino trigger latched when NHIT for event exceeds prescribed threshold
OWL	Outward Looking PMTs
PA	PCS preamplifier
P10	90% Ar/ 10% CH ₄ PCS fill gas
PC	Polycarbonate
PCC	Polycarbonate cylinder housing the PCS cartridge
PDF	Probability Density Function
PM	PCS pressure sensor
PMT	Photomultiplier tube
PMTIC	PMT Interface Card
PPNIM	Pulse Processing Module
PSUP	Photomultiplier Support Structure
QC	Quality Control
QA	Quality Assurance
RSP	Energy processor used in SNOMAN
SNOMAN	SNO Monte Carlo and Analysis Code
SS	PCS Stainless Steel Assembly
Th	The element Thorium used interchangeably with ²³² Th
U	The element Uranium used interchangeably with ²³⁸ U
UPW	Ultra-pure Water
URM	Universal Retrieval Mechanism
UVT	Ultraviolet Transmitting Plastic

Table 1 : *Table of acronyms used in this thesis*

Unit	Meaning
psi	Unit of pressure (pounds/inch ²) 1 atm = 14.7 psi
psia	Same as psi except pressure expressed relative to vacuum
mwe	Meters Water Equivalent unit used to express rock overburden
Bq	1 disintegration / second
NHIT	Number of PMT's firing in a 100×10^{-9} s coincidence
ppm	parts-per-million
k	1000

Table 2 : *Table of units used in this thesis*

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Chapter 1

Overview of Thesis

1.1 The Solar Neutrino problem

It is now believed that the physics of how the sun works is well understood. However, since the 1960's, it has been observed that the measured solar neutrino (ν) flux is less than what is expected from the theory of solar energy production. Indeed, the predictions by current theory known as the standard solar models (SSM) ¹ agree well with observations. However, there is one observation that has not been consistent with the suggestions by the SSM's: the neutrino flux due to energy production in the sun is not what is expected. A discrepancy of experiment [1] with calculation became evident in the late 1960's when 1/3 of the ν 's were observed as compared to the predictions by the SSM's [2]. In this experiment known as the Homestake experiment [3], solar neutrinos were detected by collecting the radioactive argon isotope produced in the transmutation of ^{37}Cl atoms to ^{37}Ar . Later new experiments came on-line: SAGE [4], GALLEX [5], Kamiokande [6], and Super-Kamiokande [7], all of which

¹The SSM is a model which based on certain assumptions correctly predicts the observed solar characteristics such as the solar luminosity, radius, as well as recent information about helioseismology. It makes direct quantitative predictions for the flux and energy spectrum of solar ν_e 's, which is the theoretical standard that all solar ν experiments are compared to.

supported the claim of the Homestake experiment that the measured solar neutrino flux was significantly lower than predicted by SSM's. This deficit became known as the solar ν problem (SNP) and was one of the long-standing problems of high energy physics. The SNP, SSM's, and solar neutrino experiments are discussed in more detail in Chapter 2.

Rather than artificially adjusting various parameters in the SSM to fit the data, a new mechanism was proposed that suggested that not all is known about the propagation of electron ν 's (ν_e) through space and matter. The possibility was raised that upon travelling through the solar interior and space, ν_e 's change into ν 's of other flavours (such as μ or τ). This mechanism is called neutrino oscillations and renders the ν_e 's undetectable by then active solar ν experiments. For ν oscillations to occur, it is required for ν 's to have mass, a reasonable extension to the Standard Model of particle physics. Solar neutrino experiments and neutrino oscillations are discussed in Chapter 2.

1.2 The Sudbury Neutrino Observatory

To resolve the SNP, it became clear that a measurement must be made independent of the SSM to test various solutions to the SNP. This measurement was realized with the construction of the Sudbury Neutrino Observatory (SNO) deep in a mine in Ontario, Canada. SNO [8, 9] has as its active volume heavy water, and as such, it is not only sensitive to reactions involving ν_e 's (such as the charged current (CC) reaction to be described later) but it is also sensitive to ν 's of other flavours through the flavour blind neutral current (NC) reaction. SNO observes ν 's by a sphere of 9600 photomultiplier tubes (PMTs) that surround the heavy water, and detect the Čerenkov radiation produced by electrons (e^-) and gamma rays (γ) that are emitted as a result of ν interactions. Each type of ν interaction has a specific signature, which allows us to separate the CC from the NC events, and thus measure the flux of each reaction separately. This along with the fact that the ν interaction cross sections are well known for heavy water allows

an entirely SSM independent comparison to be made of the solar ν flux of various flavours. The Sudbury Neutrino Observatory is discussed in more detail in Chapter 3.

1.3 The Proportional Counter Source

To accomplish the CC and NC measurements, the low energy background in SNO must be known to high precision. The low energy background is mainly due to the decay of beta (β) emitters in the ^{232}Th and ^{238}U chains (Th and U) inherent in the detector components. These betas produce Čerenkov radiation that masquerades as the Čerenkov light produced by a neutrino interaction. The low energy background appearing as an exponential increase towards lower energies is known as the "background wall". The shape of the background wall determines the low energy threshold of neutrino detection and tells us the fraction of the neutrino spectrum that SNO is sensitive to.

Determination of the shape of the background wall is to be attained by using a proportional counter (hereafter referred to as PCS) with various beta emitters from the ^{232}Th and ^{238}U chain placed on the anode. When the proportional counter is placed in the SNO active volume, the $\beta - \gamma$ cascade that is produced by the decay of the source on the anode will produce Čerenkov radiation, just as the decay of the same isotope present in the heavy water would. The surrounding SNO PMTs that detect the Čerenkov radiation will then pick up the signal. The main advantage of the technique is that the signal due to the isotope can be determined independent of other beta-emitters because by tagging the beta in the proportional counter other backgrounds can be neglected. The focus of this thesis is the development, construction, testing, analysis and deployment of the PCS.

1.4 The Organization of the Thesis

The organization of this thesis is the following. Chapter 2 discusses the standard solar model (SSM), solar neutrino experiments and the solar neutrino problem (SNP). Chapter 3 introduces the SNO detector and explains how SNO has solved the solar neutrino problem. Chapter 4 focuses on the various backgrounds present in the SNO detector and motivates the necessity for the PCS. In this chapter the main design criteria of the PCS are presented. These main criteria are:

- [1] PCS cannot pose a risk to SNO
- [2] PCS ^{228}Th source activity must be known with high precision
- [3] PCS can be triggered or tagged so that its contribution can be identified with respect to the rest of the triggers.
- [4] PCS position must be well determined in SNO
- [5] PCS must closely approximate a ^{228}Th point source

Chapter 5 introduces the general theory of the proportional counters and follows with a component-by-component description of the design. The remainder of the chapter focuses on the testing, Quality Control (QC) and Assurance (QA) and safety precautions built in the PCS design. In this sense, Chapter 5 intends to persuade the reader that the most important design criterion that the *PCS will not pose a risk to SNO* has been met. Chapter 6 deals with the rest of the design criteria. First experimental measurements are described that allow the PCS source activity to be extracted with high precision. This investigation has also shown that the PCS can be triggered with a high efficiency. The remainder of the chapter discusses the implementation of the PCS geometry into the SNOMAN monte carlo code, the main monte carlo and analysis package used by the SNO collaboration. Monte Carlo and engineering run data is used to suggest that the PCS closely approximates a point source. Chapter 7 discusses the procedures

and the run plan for deployment of the PCS in the H₂O and closes with a general discussion of the PCS analysis.

Chapter 2

The SSM, SNP and First Solar Neutrino Detectors

2.1 Introduction

The first evidence for neutrino oscillations came from the Homestake [1, 3] Chlorine experiment where it was shown that the measured solar neutrino flux was significantly lower than what was predicted by the standard solar model. The Homestake [10] data was later reinforced by other solar neutrino experiments that came on-line such as SAGE [4], GALLEX [5], GNO [11], Kamiokande [6] and in the late 1990's Super-Kamiokande [7]. The significance of the solar neutrino deficit as observed in these experiments is shown in Table 1. The table shows the ratio of the experimentally obtained neutrino flux ($\phi_{exp} \pm \delta_{exp}$) to the SSM predicted value ($\phi_{SSM} \pm \delta_{SSM}$). In each experiment a deficit is evident. The significance of this deficit is expressed in the table as $\left(\frac{\phi_{SSM} - \phi_{exp}}{\sigma}\right)$, where σ is the one standard deviation error associated with adding the experimental (δ_{exp}) and SSM uncertainty (δ_{SSM}) in quadrature. Statistically significant deviation from the SSM values of neutrino flux is observed in every experiment. This discrepancy of theory and experiment is known as the solar neutrino problem.

Experiment	Home-Stake	Kamiokande	Super-Kamiokande	GALLEX	GNO	SAGE
Target	Cl	H ₂ O	H ₂ O	Ga	Ga	Ga
$\frac{\phi_{exp}}{\phi_{SSM}}$	0.33 ± 0.06	$0.55^{+0.13}_{-0.11}$	$0.47^{+0.09}_{-0.07}$	0.60 ± 0.07	0.51 ± 0.09	0.58 ± 0.07
Significance of Deviation (σ)	5.0	2.9	3.8	5.3	5.2	5.4
Type	EI	EI	DE	EI	EI	EI
Reaction	CC	CC+NC	CC+NC	CC	CC	CC

Table 2.1 : *This table shows the ratio of the measured solar neutrino flux from various experiments to the flux predicted by the Standard Solar Model of Bahcall, Pinsonneault and Basu [12]. Also shown is the significance of the deviation of the measured flux from the theoretical flux as explained in the text. The type of experiment (EI=integral over energy spectrum, DE=differential energy spectrum) and what type of neutrino interaction with target medium are also indicated. The references to the data are those given in the text. This table is adapted from [13]*

There are essentially two classes of solar neutrino experiments: the radiochemical experiments such as Homestake and the Čerenkov detectors such as the Kamiokande experiments and SNO. In the former, the neutrinos are detected by chemically extracting the atoms that have been transformed from one element to another by a neutrino interaction onto a target medium (See Table 2.1 for the specific targets). The second class of experiments is the Čerenkov experiments where the experiments detect in real time the interaction of a neutrino with the active medium, H₂O/D₂O, by the detection of Čerenkov light from the products of the interaction. Before we discuss these experiments in more detail, it is important we understand the Standard Solar Models (SSM) which are used to predict the spectra and flux of solar neutrinos independent of neutrino oscillations.

Since the anomalous result of the first solar neutrino experiment was published 34 years ago, the number of solar models has exploded. In an effort to constrain the models, the models

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Spherical Symmetry and Homogeneous

The SSM assumes that the sun is spherically symmetric and will not change its mass during the life of the sun. The SSM also assumes that initially the sun was highly convective and turbulent, mixing the elements so that the composition was essentially homogeneous.

Energy transport by photons or convective motions

The energy transport mechanism is assumed to be mainly by photon diffusion out of the inner core and convective motions nearer to the solar surface. The rate of energy transport depends critically on the radiative opacity, which is a complex quantity to calculate since it must account for all the microscopic processes that can absorb photons for all the elements present in the sun. These interactions are summarized in the ‘Rosseland mean opacities’ which constrain the radiative energy transport and thus temperature in the sun.

Elemental Abundance changes by nuclear reactions

While the initial solar interior is considered to be elementally homogeneous, the assumption is that changes in the abundance of elements are primarily due to nuclear reactions. It is also assumed that the abundance of metals on the solar surface has not changed since the sun entered the main sequence. The fraction of He/H is one of the free parameters in the model that is adjusted to reproduce the present day solar luminosity.

Energy generation by nuclear fusion

The assumption is that the principal method of energy generation is through the pp-chain and the CNO cycle described in the next section. The sun is essentially a slow reactor. With a central temperature of $T_c = 1.5 \times 10^7$ K, the energies of the reacting nuclei are ~ 10 keV which is far less than the Coulomb barrier that inhibits nuclear fusion. Thus, reaction cross sections

require measurements to be performed at higher energies. They must then be extrapolated to lower energies which may add uncertainties to the model.

2.2.2 Solar neutrino Production

When a star like the sun entered the main sequence an estimated 4.57 billion years ago, it started the quasi-static process of hydrogen burning in the central regions. The principal method is to fuse 4 protons into an α -particle particle, two positrons and two electron neutrinos(ν_e) with the release of 26 MeV. The main set of reactions through which this occurs is through the pp-chain (see Figure 2.1) which generates approximately 98.5% of the solar luminosity and the CNO cycle which generates the remaining 1.5%. The CNO cycle which stems from positron decay of ^{13}N , ^{15}O and ^{17}F is of minor importance for the Sun and is not discussed further. In this scheme of energy production only 2% of the energy is in the form of electron neutrinos, the kinetic energy of the other particles is eventually converted to photons which produce the radiation pressure required to support the state of hydrostatic equilibrium.

The main process essentially occurs when two protons undergo the weak interaction and produce a deuteron with the release of a low energy neutrino of maximum energy 0.423 MeV.

$$p + p \rightarrow d + e^+ + \nu_e \quad \text{pp} - \nu \text{'s } E_{\nu_e} = 0.423\text{MeV}$$

A much rarer (1 in 250) process is when a deuteron is created by the fusion of 2 protons in the presence of an electron. In the latter process the result is that a 1.442 MeV neutrino is emitted.

$$p + e^- + p \rightarrow d + \nu_e \quad \text{pep} - \nu \text{'s } E_{\nu_e} = 1.442\text{MeV}$$

The deuterons fuse with a proton and produce ^3He plus a γ -ray. The resulting ^3He may fuse 86% of the time with ^3He producing an α -particle and two protons with no further neutrinos.

Figure 2.1 : *The pp-chain of solar energy production*

Alternatively, it may fuse with ^4He to produce ^7Be plus a γ -ray. Then, the dominant reaction is for ^7Be to react with an e^- to produce neutrino energies of either 0.385 MeV (10%) or 0.861 MeV (90%).

The much rarer possibility (0.11%) is that the ^7Be fuses with a proton to produce ^8B and release a neutrino when ^8B beta decays.

While this reaction is rare, this is the principal neutrino reaction probed in active solar neutrino experiments because the energy of the neutrinos is a continuum with an endpoint at 13.7 MeV.

This exceeds the threshold of all of the radiochemical and water Čerenkov neutrino detectors. The last extremely rare possibility is that the ^3He fuses with a proton, releasing an electron and a neutrino with a continuous spectrum and endpoint at 18.8 MeV. This occurs for twice in every 10^7 terminations of the pp-chain and is not discussed further.

The predictions by the Standard Solar Model of the neutrino fluxes for each of the neutrino producing fusion reactions in the sun is shown in the table 2.2 below.

Neutrino Reaction	Chain/Termination	Flux in $10^7 \text{ cm}^{-2} \text{ s}^{-1}$
pp- ν_e	pp	$5.95 \times 10^3 (1.00 \pm 0.01)$
pep ν_e	pp	$14.0 (1.00 \pm 0.01)$
$^7\text{Be} \nu_e$	pp-II	$477 (1.00 \pm 0.10)$
$^8\text{B} \nu_e$	pp-III	$0.505 (1.00^{+0.20}_{-0.16})$
hep ν_e	pp-IV	9.3×10^{-4}
N ν_e	CNO	$54.8 (1.00^{+0.21}_{-0.17})$
O ν_e	CNO	$48.0 (1.00^{+0.25}_{-0.19})$
F ν_e	CNO	$0.563 (1.00^{+0.25}_{-0.25})$

Table 2.2 : *The measured solar neutrino fluxes predicted by the Standard Solar Model of Bahcall and Pinsonneault [12] for various neutrino sources.*

The reaction rate per unit volume for a 2 particle nuclear fusion reaction is given by dn_{ab}/dt :

$$dn_{ab}/dt = n_a n_b \langle \sigma(v) v \rangle$$

where n_a and n_b are the particle densities and $\sigma(v)$ the reaction cross-section. At the solar core the average thermal energy of particles is only several keV, which is much less than the Coulomb barriers that are of the order of MeV. Thus, the only way the reaction can occur is through quantum mechanical tunnelling. The convolution of the quantum mechanical tunnelling factor increases with energy and the high energy tail of the Maxwell-Boltzman distribution which describes the number density of the particles involved ensures that there is an

energy window where the reaction probability is non-negligible. This region is known as the Gamow peak and is of the order of 10 keV for reactions of the pp-chain. The reaction cross section is often parameterized in terms of a slowly varying function with energy known as the astrophysical S-factor ($S(E)$):

$$\sigma(E) = (S(E)/E) \exp(-\sqrt{E_g/E})$$

where E_g is the Gamov energy $E_g = (\pi\alpha Z_a Z_b)^2 mc^2$, Z_a and Z_b are the atomic numbers of the fusing particles. In this parametrization the energy dependence of the cross section evolves slowly and can be extrapolated to the lower energies relevant to Hydrogen burning from experiments conducted at lab energies [15]. The uncertainty in determining the nuclear fusion cross-section is dominated by the uncertainty in this extrapolation.

2.2.3 Uncertainties in SSM

Opacity and Equation of State

The opacity parameters determine how efficiently photons transport energy from central layers to the surface. These parameters are important for determining the radial temperature profile of the sun. It was found that there exists a relationship between the solar neutrino flux of various branches of the pp-chain and the central solar temperature (T_c). For example, it was found that the flux of ${}^7\text{Be}$ neutrinos scales as T_c^8 and that the ${}^8\text{B}$ neutrino flux scales as T_c^{18} . Consequently, the solar neutrino fluxes are extremely sensitive to T_c . Since the temperature is related to the efficiency of energy transferred out of the central region, the solar neutrino flux is sensitive to the opacity. In the latest version of the SSM [12], the best numbers for various input parameters in the model are used. The equation of state and opacity are taken from the Los Alamos OPAL calculations [17, 18] and have been recently updated to include improved

estimations of photospheric elemental abundances. Helio-seismology has allowed the intermediate region between the central region and the surface to be probed since the speed of sound is sensitive to both the opacity and the equation of state of the medium. As will be shown later, there is excellent agreement in the predicted sound speed by the most recent version of the SSM and the measured sound speeds. Therefore, the solar neutrino flux calculations can be considered to be robust with regard to the opacity and equation of state uncertainties.

Nuclear Fusion Cross-Sections

As was mentioned the extrapolation of nuclear cross-sections at lab energies to solar temperatures leads to a large amount of uncertainty. These uncertainties have led researchers in the past to speculate that the SNP can be solved by suggesting that nuclear cross-sections are lower than experimentally predicted. However, there still remains considerable uncertainty and controversy in our knowledge of these cross-sections. For example, the data are lacking for the ${}^7\text{Be}$ -p reaction (corresponding to S_{17}) which is the parent to the rare ${}^8\text{B}$ reaction which produces the ${}^8\text{B}$ neutrinos. This is due to the fact that there exists a low energy resonance (600 keV) in the cross-section making the low energy prediction for the cross-section problematic. In a workshop at Institute of Nuclear Theory 1997, the values and uncertainties in the various nuclear fusion reactions were evaluated. At the workshop, it was decided that the best documented experiment was to be adopted for the low energy extrapolation of S_{17} , rather than the world average of various measurements. This had the effect of increasing the ${}^8\text{B}$ neutrino flux by 1.1σ from the previous values. In recent years, there has been a lot of criticism of the experimental method used to determine the value for S_{17} , such as claims that the effective thickness of the ${}^7\text{Be}$ target is not well known, the effect of ${}^8\text{B}$ back scattering out of the target [19] and other systematics have not been properly taken into account. A very recent determination by Junghans *et al.* [20] of S_{17} has tried to answer this criticism by experimentally determining the effect of these systematic errors. While the value obtained is still within the error of the previ-

ously recommended value (value used in BP2000), it is 17% higher with a quoted uncertainty of 3.8%. If this measurement will withstand scrutiny, this will mean that the S_{17} measurement will not constitute the greatest uncertainty in the ^8B neutrino flux measurement.

Another difficulty important at low energies is due to atomic screening in terrestrial experiments. The measured cross-section is enhanced compared to the bare nucleus cross-section found in solar environments because of screening caused by bound ions in an ion beam and target. It is now believed that these enhancement factors are understood and can be calculated.

Other Sources of Uncertainty

The main changes in the evolution of the SSM model have been the inclusion of more up-to-date values for various nuclear cross-sections and input parameters. However, some of the assumptions in the previous sections have been relaxed in order to determine the contribution of these assumptions to uncertainties in various observable quantities, such as the neutrino fluxes and the helio-seismological parameters. The most significant addition to early SSM's was the inclusion of Helium and heavy element ($A > 5$) diffusion [21] and gravitational settling in the solar core. This was neglected in the past [14] since the diffusion occurs on a long (10^{13} years to solar radii) time scale and the calculation of these effects is very complex. This assumption has recently been validated in helio-seismological measurements. However, non-standard models which all try to lower the temperature of the sun, such as introducing strong mixing in the solar core, or rapid core rotation have largely been invalidated [12].

2.2.4 The SSM Calculation

The calculation is carried out by using the simplifying assumptions of the previous section and taking the values for various physical parameters, such as the initial helium abundance, nuclear parameters, equation of state and radiative opacities, as inputs into the model. With the

Figure 2.2 : *This figure shows the steps involved in SSM calculation*

assumption that the sun is initially homogeneous, the hydrostatic pressure, energy production and energy transfer equations are simultaneously solved in increasing time steps. As the model evolves, the abundance of the elements will change in the solar core since the hydrogen is being transmuted into heavier elements through the pp-chain and CNO cycle [15]. The model is calculated for different radial shells with increasing steps of time until the present age of the sun is reached. Various predictions can then be made for quantities like the initial helium abundance, central temperature, density and hydrogen abundance. The model is then re-iterated and the models free parameters adjusted until the constrained parameters, such quantities such as the current luminosity, radius and mass, exactly match those of observations. When this condition has been met, the neutrino fluxes from the various branches of the pp-chain as a function of radius and various helio-seismological parameters can be predicted. This calculation is summarized in Figure 2.2.

Figure 2.3 : *This figure shows the excellent agreement between the calculated (solar model BP2000 [12]) and the measured solar sound speeds as a function of the fractional solar radii [22, 23]*

2.2.5 Successes of SSM

The SSM is considered to be robust because of several reasons. The first comes from the naive determination of the solar neutrino flux which simply divides the measured luminosity by the energy released per neutrino for two neutrinos of the pp-chain. This determination leads to a flux of the order of what is experimentally measured. Another important success is the measurement of solar oscillations in the form of standing acoustic waves with frequencies depending on the sound speed. These measurements allow the determination of Helium abundance and the depth of the convective layer, both of which are in very good agreement with BP SSM. The measured fractional difference between the sound speed calculated for BP SSM and the sound speeds measured by 6 helio-seismological experiments is shown in Figure 2.3.

Furthermore, helio-seismological measurements can make predictions about the flux of ${}^7\text{Be}$ neutrinos. The argument is that ${}^7\text{Be}$ branch termination produces a large fraction of the ${}^4\text{He}$

near the solar center. This implies that if the ${}^7\text{Be}$ neutrino production is suppressed there should be less ${}^4\text{He}$ near the center, so that the sound speed decreases. Since the helio-seismological measurements near the center are in good agreement with the SSM, we know that the ${}^7\text{Be}$ neutrino production can not be much less than predicted. The unarguably greatest success of the SSM is the measurement of the total neutrino flux by SNO announced in April 2002 [24]. This is described in more detail later in Chapter 3.

2.3 General Requirements of a Solar Neutrino Detector

Several experiments have been performed to detect ν_e 's and test how energy is generated in the sun. The irony is that what makes ν 's useful as a technique for determining information about the center of the sun, the low interaction cross section of ν with matter, makes the detection of these particles very difficult. The typical cross section for ν absorption reactions is of the order of 10^{-45} cm^2 , so, to raise the probability that a ν_e is observed, a very large active volume detector is required. Furthermore, these detectors must be built deep within a mine, so that the backgrounds from cosmic rays are negligible. Another important feature of all solar neutrino experiments is the necessity to have low intrinsic radioactivity of the detecting medium, consequently the backgrounds due to these isotopes are a small fraction of the signal. Since the signal in the best solar neutrino detectors is less than 10-30 neutrinos per day, and these detectors are at least 1 kT (1000 tonne), it means that the acceptable neutrino background is several events/kT/day. Therefore, if every decay of natural radioactivity is a potential neutrino background then we require a background concentration of approximately $10^{-18} \text{ g } {}^{232}\text{Th} / \text{g}$ detecting media ⁴. In actuality, the requirement is not as stringent as $10^{-18} \text{ g } {}^{232}\text{Th} / \text{g}$ detecting media since solar neutrino experiments employ an energy threshold which avoids most of the background due to natural radioactivity, and experiments can discriminate against many

⁴A useful rule of thumb is that 1 decay /day/tonne corresponds to $\sim 10^{-15} \text{ g } {}^{232}\text{Th} / \text{g}$ detecting media

of these background events. However, even a 1000 times this background is a tremendous technical challenge for any solar neutrino detector to meet.

Currently, five solar neutrino experiments are in operation and may be divided into 2 classes. First, there are the radiochemical detectors that detect ν 's by extracting the resultant nuclei produced by the ν absorption reactions. These detectors only give information about the absolute flux above a detector energy threshold and the temporal variations in the ν_e flux on a time scale of months. Second, are the real-time direct counting experiments that detect electrons and γ -rays produced by the initial neutrino interactions. These detectors not only give information about the ν flux but also about the differential energy spectrum of the ν sources. They are also sensitive to temporal variations from nanoseconds to months.

2.3.1 Charged Current vs Neutral Current Detection

The weak interaction can be mediated either by the neutral current Z^0 bosons or the charged $W^\pm$ bosons. Their participation in a reaction constitutes the reaction as either a charged current (CC) or neutral current (NC) reaction. Inverse beta decay is a decay of the CC type:

$${}^A_Z X + \nu_l \rightarrow {}^A_{Z+1} Y + l^- \quad (2.1)$$

where X,Y are the parent and daughter respectively and l represents a lepton of any flavour. The kinematic threshold for this reaction is given by the masses of the particles involved as:

$$Q = M_Y - M_X + M_l \quad (2.2)$$

However, if the flavour is changed as the neutrinos travel from the sun to the earth, the reaction above is kinematically forbidden since the smallest lepton mass other than the electron is the muon with mass $M_\mu = 106.95$ MeV. All of the first generation solar neutrino detectors use the

CC as a mode of detection (see Table 2.1).

Neutral current reactions, on the other hand, are possible with all neutrino flavours and thus measurements with the neutral current reaction allow the total neutrino flux to be measured independent of flavour. This is the purpose of recently active direct counting neutrino experiments such as Kamiokande, Super-kamiokande and in particular SNO, to be discussed in Chapter 4. Kamiokande and Super-kamiokande use the mixed CC+NC elastic scattering reaction $\nu_l + e^- \rightarrow \nu_l + e^-$, where l can be any of the lepton flavours. The ratio of the cross-section of electron flavour to other flavours is:

$$\frac{\sigma_{\nu_e e}}{\sigma_{\nu_\mu e}} \sim 6 - 7 \quad (2.3)$$

therefore the elastic scattering has some sensitivity to other neutrino flavours. The cross-section is higher for $\nu_e e^-$ elastic scattering than the other neutrino flavours because in addition to the t-channel Z^0 exchange, $\nu_e e^-$ scattering may also occur through t-channel W boson exchange. An example of a purely NC reaction is the dissociation of deuterium by solar neutrinos of all flavours: $\nu_l + d \rightarrow \nu_l + p + n$. The Sudbury Neutrino Observatory uses this reaction and the CC reaction $\nu_e + d \rightarrow e^- + p + p$ to determine the flavour components of the solar neutrino flux. This is described in more detail in Chapter 4.

2.4 First Generation Solar Neutrino Experiments

2.4.1 The ^{37}Cl Experiment

The first experiment to detect ν 's from the sun is the radio-chemical experiment by Davis *et al.* [3, 10]. The experiment was based 1490 m underground in the Homestake Gold Mine (4900

m.w.e. ⁵). The experiment uses 0.615 kt perchloroethylene (C₂Cl₄) which has 133 tons ³⁷Cl as its target for the ν_e absorption reaction. The experiment utilizes the ν absorption reaction:

This reaction has a Q-value of 0.814 MeV, so the experiment is sensitive to all ν_e 's coming from the sun, except for the pp- ν 's (reaction 1 in Table 2.2) and the 0.38 MeV ⁷Be line (see Figure 2.4). This experiment has been running continuously ⁶ since 1967.

2.4.2 The ⁷¹Ga Experiments

The pp- ν 's are expected to have the highest flux with the least uncertainty, it has long been a goal to detect these ν_e 's. The problem is that pp- ν 's have a very low endpoint (422 keV) and the large detector backgrounds, which makes these ν 's very difficult to detect. The GALLEX, SAGE and GNO Collaborations have utilized the reaction:

which has a Q-value of 0.233 MeV, and makes it sensitive to pp- ν_e 's.

GALLEX

The GALLEX experiment [5], situated at Gran Sasso underground laboratory (3300 m.w.e.), uses 30.3 tons of Ga as a solution of GaCl₃ in HCl. The ⁷¹Ge that is produced due to the neutrino reaction is extracted as GeCl₄ and chemically converted to the gas germane (GeH₄), a

⁵mwe stands for meters water equivalent and is a method of comparing the amount of shielding provided by the rock overburden for various solar ν detectors.

⁶Except for a 17 month period in 1985/86 when there were failures in the circulation pumps

Figure 2.4 : The figure shows the predicted spectrum of solar ν 's according to the Bahcall-Pinsonneault SSM [12]. Figure courtesy of J. N. Bahcall

methane like gas. The gas is used both as the ^{71}Ge radioactive source and as a counting gas in a miniature proportional counter when mixed with Xe.

SAGE

The second ^{71}Ga experiment is the Russian American Gallium Experiment (SAGE) [4] which is located at the Baksan Neutrino Observatory (4700 m.w.e.) and has been taking data since 1990. It is very similar to GALLEX in the extraction of the ^{71}Ge , except that 55 tons of pure gallium metal is used instead of a GaCl_3 solution. This has the added advantage that the

experiment is less susceptible to radioactive impurities and since the volume is much smaller reduces the backgrounds present. The SAGE experiment extracts the ^{71}Ge from the gallium metal and as is done in the GALLEX experiment, the Ge is converted to germane, added to xenon gas and inserted into a proportional counter. Unfortunately, even though the target mass is almost twice that of GALLEX, the error in the measurement does not reflect this. This is because the SAGE experiment has suffered from some unknown systematics.

Both experiments have calibrated their neutrino detection efficiency using a ^{51}Cr low energy neutrino source, and the ratio of neutrino detected to what was expected was close to one in both experiments (GALLEX: 0.94 ± 0.08 , SAGE: $0.95 \pm 0.12(\text{exp})^{+0.035}_{-0.027}(\text{theor})$). Therefore, the measured discrepancy (see Table 2.1) cannot be attributed to systematic errors in the analysis of the Ga results.

GALLEX was in operation from 1990 to 1997 and was discontinued to allow the installation of its successor, GNO, in 1998. GNO [11] is a upgraded version of GALLEX with a target consisting of 101 tons of a GaCl_3 solution in water and HCl , containing 30.3 tons of natural gallium. The latest results for the Ga experiments, along with how these compare with theoretical calculations, are shown in Table 2.1.

2.4.3 Kamiokande

The Kamiokande ⁷ experiment is located 1 km below ground, in a mine in the Japanese Alps (2700 m.w.e.). It is a real-time, direct counting, water Čerenkov experiment employing 4.5 kt H_2O as its active volume. The inner 2.14 kt is viewed by 948 Hamamatsu 51cm PMTs, providing 20% photo-cathode coverage. The fiducial volume is a cylinder of radius 4.0 m and height 5.2 m corresponding to 0.68 kt H_2O . This is surrounded by a 1.5 m layer of water and by 123 PMTs, which detect cosmic ray muons passing through the water and consequently

⁷The Kamiokande [6] experiment has gone through several generations of upgrades denoted by KI, KII and KIII

veto the inner detector, consequently these events are ignored. Kamiokande is sensitive to the highly forward elastic scattering (ES) reaction:

$$\nu_e + e^- \rightarrow \nu_e + e^- \quad (2.6)$$

by detecting the Čerenkov radiation produced by the recoiling e^- 's. The low energy background wall fixes the energy threshold above 7.5 MeV, therefore the Kamiokande experiments are only sensitive to ${}^8\text{B}$ ν 's⁸. Because of Kamiokande's directional sensitivity (angular resolution 28° to 20° from 10 to 20 MeV respectively [25]), they were the first to positively prove that the sun is a source of ν_e 's. The data and its comparison to theoretical calculations, are shown in Table 2.1. The data was continuously taken from 1987 to 1995 when it was stopped to allow for the installation of Super-Kamiokande, which is discussed later in this chapter.

2.4.4 The Solar Neutrino Problem

A quick glance at Table 2.1 reveals a clear discrepancy of theory with experiment which is known as the SNP. The table can be re-cast in the form of a diagram (see Figure 2.5) which shows where a breakdown of the measured and theoretical event rates are shown and which solar neutrinos are detected, as a function of neutrino detection technique. First it is observed that the Chlorine experiments which essentially measures the ${}^8\text{B}$ neutrino flux, with minor contributions from the ${}^7\text{Be}$ and CNO neutrinos, is lower than what was expected. This was the original SNP. At this stage doubt was cast on whether the ${}^8\text{B}$ ν_e flux was calculated correctly in the SSM.

A series of 1000 Monte Carlo calculations [26] were done, in which the input parameters to the SSM were randomly sampled from a Gaussian distribution with the mean given by the

⁸Kamiokande is also sensitive to hep ν 's (see reaction 5 in Table 2.2) as well, but these have a flux three orders of magnitude less than the ${}^8\text{B}$ ν 's.

Figure 2.5 : *This figure shows the experimental and theoretical rates for various solar neutrino experiments. Figure courtesy of J. N. Bahcall*

experimental estimate for that parameter. It was shown that even in the best case scenario (in the low flux tail of the 1000 SSM distribution), the separation is still very evident for both experiments (See Figure 2.6 and Figure 2.7 below). Furthermore, if the ⁸B flux in the 1000 SSM's were changed artificially such that the Kamiokande ⁸B ν flux would be the input parameter, the 1000 SSM's would still not agree with the Cl experiment. Not only were the experiments not agreeing with the SSM, but also they were not even agreeing with each other. As a consequence of this inconsistency, it was believed that one of the experiments was incorrect. It was argued that since neither experiment had been calibrated with a ν source, there would be too many systematic errors that have not been anticipated.

Figure 2.6 : J.N. Bahcall's 1000 solar models for the chlorine experiment. Courtesy J. Bahcall [26]

Figure 2.7 : J.N. Bahcall's 1000 solar models for the Kamiokande experiment. Courtesy J. Bahcall [26]

The second solar neutrino problem is that when the Kamiokande experiment came on-line, there was an inconsistency between the Chlorine experiment and the Kamiokande experiment. This was a more severe incompatibility because Kamiokande measures only the ^8B solar neutrino flux with no contribution from the other solar neutrino sources. Kamiokande measured more solar neutrinos from the ^8B neutrinos than the Chlorine experiment, which measures contributions from other neutrinos, such as ^7Be neutrinos. This leads to a new problem: how can the ^7Be neutrinos be suppressed more than the ^8B neutrinos when ^7Be is needed to produce them.

In the 1990's the Ga experiments (GALLEX and SAGE) started counting, which were sensitive to p-p, ^7Be and ^8B neutrinos. These measurements as Figure 2.5 shows, demonstrated that not only were the ^8B neutrinos suppressed, the ^7Be ν 's were completely missing⁹ even though the ^8B ν 's are only created through the ^7Be reaction. Thus, it would be expected that there should be at least as many ^7Be ν 's as ^8B ν 's. In a paper (appropriately entitled *Where are the Beryllium Neutrinos?*) Degl'Innocenti, Fiorentini and Lissia [27] express the SNP very clearly. With a few minor assumptions¹⁰ and assuming that the results from all 4 solar ν experiments are correct, they extract the experimentally obtained ^7Be ν flux ($\Phi_{^7\text{Be}}$) and the flux due to the CNO cycle ν 's (Φ_{CNO}). They obtain a ^7Be ν flux of $\Phi_{^7\text{Be}} = 4.9 \pm 3.4$ SNU and a negative value for the CNO ν 's of $\Phi_{\text{CNO}} = -5.7 \pm 5.6$ SNU. If we constrain the CNO ν flux to be zero¹¹, the physical $\Phi_{^7\text{Be}}$ consistent with all four experiments is negative. This is shown in Figure 2.8 where the experimental results are shown for each experiment (with areas defined as the areas allowed at 1σ) in the $\Phi_{^8\text{B}} - \Phi_{^7\text{Be}}$ plane, with the assumption that $\Phi_{\text{CNO}} = 0$. Here

⁹The assumption is that the pp- ν flux is as is expected by the SSM. This assumption is acceptable since it is expected that 98% of the ν 's emitted by the sun are pp- ν 's.

¹⁰The luminosity is the observed solar luminosity and the average energy carried off by the ν 's in each reaction is as predicted by nuclear physics. Also, various flux ratios were taken from SSM values. However, studies were done where the input parameters were varied wildly from the range defined by SSM and Non-SSM (NSSM), these flux ratios remain practically constant.

¹¹We must demand the flux to be physical and with $\Phi_{\text{CNO}} \sim 0$ it is the best case scenario for the SSM. ie. closest to the predictions by the SSM

Figure 2.8 : *The regions allowed in the $\Phi_B - \Phi_{7Be}$ plane by the present experimental results. Dashed lines correspond to central values, solid lines denote 1σ limits. The diamond shows the central value of the SSM of Degl'Innocenti, Fiorentini and Lissi, along with the 1σ error bars. [27]*

it is seen that the allowed areas of all 4 experiments intersect in the non-physical region where Φ_{7Be} is negative.

2.5 Proposed Solutions: Now Discounted Solutions

After the first generation of solar neutrino experiments, various solutions were proposed. The first solution was that one or several of the solar neutrino experiments did not estimate their systematics correctly. Consequently, one or more of the experimental results are wrong. Referring to Figure 2.8, it can be seen qualitatively that if one of the experiments is rejected, the intersecting 1σ regions of the other experiments are still unphysical. This was studied by Degl'Innocenti, Fiorentini and Lissia [27] by performing a χ^2 analysis under the con-

Figure 2.9 : *Confidence level curves in the $\Phi_{8B} - \Phi_{7Be}$ plane for: a) Cl+Ga+Kamiokande data, b) Cl+Ga data, c) Cl+Kamiokande data and d) Ga+Kamiokande data. The solid curves correspond to 90%, 95% and 98% confidence levels, while the dashed curve corresponds to confidence level at which ${}^7\text{Be}$ is negative. The diamonds show the DFL SSM prediction with one σ error bars. Taken from [27]*

straint $\Phi_{\text{CNO}} \sim 0$ ¹², where $\Phi_{7\text{Be}}$ and Φ_{8B} are free parameters. It is seen that even if two of the experiments are arbitrarily chosen to be correct and the other is excluded, the fit still chooses a $\Phi_{7\text{Be}} \leq 0$ for all of the experiments with a confidence level exceeding 45%. This is shown in Figure 2.9, where various combinations of experiments are fit [27] to the SSM of Degl’Innocenti, Fiorentini and Lissia (DFL)¹³.

Furthermore, as mentioned before, the GALLEX and SAGE experiments have successfully calibrated their efficiency with a ${}^{51}\text{Cr}$ neutrino source. The ratio of measured ${}^{71}\text{Ge}$ to the expected value, was calculated to be consistent with unity and an uncertainty of $\sim 10\%$. Therefore, a solution to the SNP assuming that one or more of the experiments is wrong seems

¹² $\Phi_{\text{CNO}} \sim 0$ is the best case for reproducing results predicted by the SSM

¹³In this report, various SSM’s have been mentioned (BP, DFL) all of which make similar predictions for the neutrino fluxes.

unlikely.

A second solution proposed, now discredited, is that our understanding of how the sun works even though the current model correctly reproduces all the observable characteristics of the sun is incorrect. One of the main empirical predictions is that the neutrino fluxes are proportional to the central temperature of the sun (T_c) raised to some power. It is predicted that in the SSM of Bahcall and Ulrich [2] the ν fluxes vary as, $\Phi_{8B} \propto T_c^{18}$ and $\Phi_{7Be} \propto T_c^8$. A class of solar models, known as non-standard solar models (NSSM), suggests that various solar parameters are not well known and may cause T_c to be lower than expected by SSM's. It is apparent that because of the high power law exponent for these fluxes, one does not have to change T_c a lot for the neutrino flux to vary considerably. For example, if the T_c is lowered by only 5%, the reduction in the neutrino fluxes would be $(.95)^{18} \sim 0.4 \Phi_{8B}$ and $\sim 0.65 \Phi_{7Be}$. In addition, Castellani *et al.* [28] show that even with NSSM's, the ν fluxes still have a power law relationship, so that T_c can be a reasonable SSM model independent parameter (See Figure 2.10). The problem qualitatively is that according to the SSM's and the NSSM's, Φ_{8B} varies with a higher power law exponent than Φ_{7Be} . However, we know that the experiments range from 0.3-0.5 Φ_{8B}^{ssm} and Φ_{7Be} is practically zero. Therefore, the Φ_{7Be} has changed more than it should have, according to the power law, and in the wrong direction (not exceeding 0.3-0.5 but less than this value). The inconsistency is that the solution to the SNP must not only explain the ratio of the experimental rates to SSM expectations of the neutrino flux, but it must also explain why the 7Be flux is completely missing even though the 8B neutrinos are the daughter of 7Be .

All these solutions mentioned in this section have been investigated and refuted by recent experimental evidence. Data from first generation solar neutrino and helio-seismological have inspired more confidence in SSM's (see section 2.2.5). However, at the time of completion of the first 'Second Generation' experiment, Super-Kamiokande [7] it was clear that the solution to the SNP pointed to a non-standard property of neutrinos, where neutrinos born as electron

Figure 2.10 : This figure shows the behaviour of Φ_{pp} , Φ_{Be} and Φ_B as a function of the central temperature T_c when varying S_{pp} , opacity, Z/X and age, all of which are NSSM's [28]

Figure 2.11 : *The Feynman diagram responsible for matter enhanced neutrino oscillations*

neutrinos can transform into neutrinos of other flavours (discussed in the next section) that are not detected by 'first generation' solar neutrino detectors. This property allowed not only the neutrinos to oscillate into different flavours so that they were not detected by solar neutrino experiments, but it could also depreciate the flux of neutrinos in an energy dependent way so that the ${}^7\text{Be}$ neutrinos could be suppressed more than the ${}^8\text{B}$ neutrinos. This solution is now the accepted solution to the solar neutrino problem because of the convincing evidence from the 'Second Generation' solar neutrino experiments which is discussed later.

2.6 Particle Physics Solutions: Neutrino Oscillations

Another proposal ¹⁴ is that the SNP is solved by the possibility that solar ν 's may change into an undetectable particle as they travel from their place of birth to the Earth. Historically, the first suggestion was that ν_e 's change as they travel through space, the so called 'vacuum oscillations'. The idea is that the ν_e is a flavour eigenstate, but is not necessarily a mass eigenstate. Rather, ν_e is a mixture of mass eigenstates. For simplicity only the two neutrino mixing case is discussed here. However, the formalism can easily be extended to include three generations of

¹⁴This section comes from references: [15], [29]

neutrinos [30, 31]. The Schrödinger equation for this system can be written as:

$$i \frac{d}{dt} \begin{pmatrix} |\nu_e\rangle \\ |\nu_x\rangle \end{pmatrix} = \begin{pmatrix} H_{ee} & H_{ex} \\ H_{xe} & H_{xx} \end{pmatrix} \begin{pmatrix} |\nu_e\rangle \\ |\nu_x\rangle \end{pmatrix} \quad (2.7)$$

where ν_x refers to any ν that is not of the electron flavour, x could be μ or τ . The presence of the off-diagonal components ensures that the flavour eigenstates are not mass eigenstates and allows for mixing between the eigenstates. The mass eigenstates $|\nu_{1,2}\rangle$ can then be written as an orthogonal mixture of the 2 flavour eigenstates:

$$|\nu_e(t)\rangle = \cos(\theta_v) |\nu_1\rangle + \sin(\theta_v) |\nu_2\rangle \quad (2.8)$$

$$|\nu_x(t)\rangle = -\cos(\theta_v) |\nu_1\rangle + \sin(\theta_v) |\nu_2\rangle \quad (2.9)$$

Now assuming that the 2 masses m_1 and m_2 are very close, we can approximate the energy of each ν :

$$\begin{aligned} E_i &= (p^2 + m_i^2)^{1/2}, i = 1, 2 \\ &\sim p (1 + (m_i^2/2p^2)) \\ &\sim p + m_i^2/2p \end{aligned} \quad (2.10)$$

Therefore, if $m_1 \neq m_2$, the two ν states will evolve differently through time and space, each state acquiring a different Einstein phase factor. Thus, the ν state evolution can be described by:

$$|\nu_e(t)\rangle = \cos(\theta_v) e^{-iE_1 t} |\nu_1\rangle + \sin(\theta_v) e^{-iE_2 t} |\nu_2\rangle \quad (2.11)$$

$$|\nu_x(t)\rangle = -\cos(\theta_v) e^{-iE_1 t} |\nu_1\rangle + \sin(\theta_v) e^{-iE_2 t} |\nu_2\rangle \quad (2.12)$$

The amplitude for an electron neutrino to remain an electron neutrino (a_e) or to convert into a neutrino of another flavour (a_x) is:

$$a_e = \langle \nu_e(t) | \nu_e(0) \rangle = \cos^2(\theta_v) e^{-iE_1 t} + \sin^2(\theta_v) e^{-iE_2 t} \quad (2.13)$$

$$a_x = \langle \nu_x(t) | \nu_e(0) \rangle = -\cos(\theta_v) \sin(\theta_v) e^{-iE_1 t} + \sin(\theta_v) \cos(\theta_v) e^{-iE_2 t} \quad (2.14)$$

Thus, the probability for the ν_e to change to ν_x can be readily calculated to be:

$$P_{\nu_e \rightarrow \nu_x}(R) = \sin^2(2\theta_v) \sin^2[\pi R/L_v] \quad (2.15)$$

where,

$$\begin{aligned} L_v &= 2\pi/(E_1 - E_2) \\ &= 4p\pi/(m_1^2 - m_2^2) \\ &= 1.657 \times 10^{-8} \left(\frac{E}{MeV} \right) \left(\frac{eV^2}{\delta m^2} \right) A.U. \end{aligned} \quad (2.16)$$

where R represents the distance the ν has travelled in time t , L_v is the vacuum oscillation length dependent on the difference of the masses squared of the two ν mass eigenstates. Consequently, a beam that is initially composed of ν_e (since this is the only flavour that will be created in the nuclear fusion reactions in the sun) will gradually change to ν_x and become undetectable by the four existing solar ν experiments. For solar neutrinos, the expression for L_v can be re-expressed in terms of the argument of the sine function:

$$\left(\frac{\pi R}{L_v} \right) = 1.9 \times 10^{11} \left(\frac{MeV}{E} \right) \left(\frac{\delta m^2}{eV^2} \right) \left(\frac{R}{AU} \right) \quad (2.17)$$

Thus, if R is the distance from the sun to the earth, and $L_\nu \ll R$, we may replace the $\sin^2$ term by its average value. So that we get:

$$P_{\nu_e \rightarrow \nu_x}(R) = (1/2) \times \sin^2(2\theta_\nu) \quad (2.18)$$

Now, if we assume maximal mixing ($\theta_\nu = \pi/4$), the probability for flavour conversion is $1/2$. However, experience with the Cabibbo angle in the quark sector suggests a small vacuum mixing angle, and then a solution to the SNP due to vacuum oscillations would be unlikely. In addition, experimental results suggest an energy dependent suppression of the neutrino flux which is not predicted by vacuum oscillations.

2.6.1 Matter Enhanced Oscillations

It has now been shown ¹⁵ that ν_e conversion to ν_x is possible without an unlikely large value for the vacuum oscillation mixing angle through a mechanism that is dependent on the density of electrons in the sun, known as the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism [35, 36]. The suggestion is that electron neutrinos upon travelling through the sun interact coherently with the electrons present in the solar interior by W-exchange (see Figure 2.11) incurring an additional potential V_c dependent on the electron density:

$$V_c = \sqrt{2}G_F N_e = 7.6Y_e \frac{\rho}{10^{14}g/cm^3} eV \quad (2.19)$$

where N_e is the total number of electrons, Y_e describes the number of electrons compared to nucleons and ρ is the local matter density in the sun.

To evaluate the effect of this additional potential, we revisit the case of vacuum oscillations and consider the extra potential V_c as a perturbation adding an effective mass to the neutrino

¹⁵This section comes from references: [32], [33], [30], [29] and [34]

as the neutrino propagates through the sun. The effective neutrino mass is transformed by the perturbation as:

$$m^2 = E^2 - p^2 \implies (E + V_c)^2 - p^2 = E^2 - p^2 + \underbrace{2EV_c}_{\text{Extra term in H}} \quad (2.20)$$

We start with the vacuum oscillations Hamiltonian (see Equation 2.7) as stated in the previous section for the two flavour formalism and solve the Schrödinger equation for the two probability amplitudes a_e and a_x .

$$i \frac{d}{dt} \begin{pmatrix} a_e \\ a_x \end{pmatrix} = \begin{pmatrix} H_{ee} & H_{ex} \\ H_{xe} & H_{xx} \end{pmatrix} \begin{pmatrix} a_e \\ a_x \end{pmatrix} \quad (2.21)$$

Taking the time derivatives of the probability amplitudes leads to an expression for the Hamiltonian of:

$$H = \begin{pmatrix} \frac{m_1^2 \cos^2 \theta_v + m_2^2 \sin^2 \theta_v}{2p} + p & \frac{\delta m^2}{2p} \cos \theta_v \sin \theta_v \\ \frac{\delta m^2}{2p} \cos \theta_v \sin \theta_v & \frac{m_2^2 \cos^2 \theta_v + m_1^2 \sin^2 \theta_v}{2p} + p \end{pmatrix} \quad (2.22)$$

Evaluating the Hamiltonian in the relativistic limit such as $E \sim p + \frac{m^2}{2p}$, we find that the Hamiltonian can be expressed as the sum of a diagonal matrix and a matrix leading to mixing of the flavours:

$$H = \frac{(m_1^2 + m_2^2)}{4p} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\delta m^2}{4p} \begin{pmatrix} -\cos 2\theta_v & \sin 2\theta_v \\ \sin 2\theta_v & \cos 2\theta_v \end{pmatrix} \quad (2.23)$$

We then add the contribution of the potential V_c to the electron flavour, such that:

$$H = \frac{(m_1^2 + m_2^2)}{4p} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\delta m^2}{4p} \begin{pmatrix} -\cos 2\theta_v & \sin 2\theta_v \\ \sin 2\theta_v & +\cos 2\theta_v \end{pmatrix} + \begin{pmatrix} 2EV_c & 0 \\ 0 & 0 \end{pmatrix} \quad (2.24)$$

$$= \frac{(m_1^2 + m_2^2 + A)}{4p} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{\delta_m^2}{4p} \begin{pmatrix} A - \cos 2\theta_v & \sin 2\theta_v \\ \sin 2\theta_v & A + \cos 2\theta_v \end{pmatrix} \quad (2.25)$$

$$= \text{Constant} + \delta \begin{pmatrix} A - \cos 2\theta_v & \sin 2\theta_v \\ \sin 2\theta_v & A + \cos 2\theta_v \end{pmatrix} \quad (2.26)$$

where,

$$\delta = \frac{\delta_m^2}{4p} \quad (2.27)$$

Note that $A \equiv V_c/2$ was added in a symmetric way so that the constant part of the Hamiltonian can be separated from the part of the Hamiltonian that mixes the neutrino flavours. Since we are interested in the mixing between the eigenstates and the splitting of the eigenvalues, we can drop the first term which only adds a constant factor to the energy for both neutrino eigenstates. We can then re-express the Hamiltonian in terms of a new matter mixing angle θ_m :

$$H = \text{Constant} + \begin{pmatrix} \delta_m \cos 2\theta_m & \delta_m \sin 2\theta_m \\ \delta_m \sin 2\theta_m & \delta_m \cos 2\theta_m \end{pmatrix} \quad (2.28)$$

where

$$\delta_m = (A^2 + \delta^2 - 2A\delta \cos 2\theta_v)^{1/2} \quad (2.29)$$

and,

$$\tan 2\theta_m = \frac{A \sin 2\theta_v}{A - \delta \cos 2\theta_v} \quad (2.30)$$

The expression above for $\tan(2\theta_m)$ reveals that a resonance occurs when:

$$A = \delta \cos(2\theta_v) \quad (2.31)$$

In terms of the solar neutrino problem, it means that at some depth in the sun the Wolfen-

stein term added to the Hamiltonian will tend to cancel the difference in the diagonal elements and hence, will lead to maximal mixing of the neutrino flavour eigenstates. The advantage of this mechanism is that no fine tuning of vacuum mixing angles is required since regardless of the size of θ_v , the resonance must occur. The second required condition is that the solar density must be high enough so that the two diagonal matrix elements can become equal. Since the solar density varies by several orders of magnitude as the neutrino travels from the neutrino production region to the surface of the sun, this condition will usually occur.

We can now calculate the ν_e survival probability $P(\nu_e \rightarrow \nu_x)$ to be:

$$P(\nu_e \rightarrow \nu_x) = \left| \sum_i \langle \nu_e | \nu_i \rangle e^{-iE_i t} \langle \nu_i | \nu_x \rangle \right|^2 = 1 - \frac{1}{2} \sin^2(2\theta_m) \quad (2.32)$$

Where the last step in the above formula was obtained by averaging over the neutrino phase in experimental situations information on the phase is lost. This picture is, however, only relevant to neutrinos propagating through constant density media. For solar neutrinos, the effective mixing angle θ_m is continuously changing as the neutrino propagates from the point of creation near the solar core to the solar surface. At the point of creation, the electron neutrino is a linear combination of mass eigenstates (denoted as A_o and B_o). However, as the neutrino exits the solar surface, it will emerge as a different combination of mass eigenstates, A_s and B_s (see Figure 2.12). In the adiabatic approximation, the state $A_o(B_o)$ will evolve into $A_s(B_s)$ 100% of the time. However, if the matter density is not slowly changing, the assumption of adiabaticity no longer holds. In this case, quantum mechanical tunnelling may allow the neutrino to jump from one eigenstate to another. This crossing probability (denoted as P_c) describes the probability that A_o will jump to B_s in the resonance region. Calculating the ν_e survival probability one gets:

$$P(\nu_e \rightarrow \nu_e) = \frac{1}{2} + \left[\frac{1}{2} - P_c \right] \cos(2\theta_v) \cos(2\theta_m) \quad (2.33)$$

Figure 2.12 : *This figure shows the masses of two flavours of neutrinos as a function of density*

Where P_c has been calculated to be:

$$P_c = \frac{\exp(\frac{-\pi}{2}\gamma F) - \exp(\frac{-\pi}{2}\gamma \frac{F(\theta)}{\sin^2(\theta_v)}}{1 - \exp(\frac{-\pi}{2}\gamma \frac{F(\theta)}{\sin^2(\theta_v)}} \quad (2.34)$$

where,

$$\gamma = \frac{\delta m^2 \sin^2(2\theta)}{2E \cos(2\theta) |dN_e/dx|} \quad (2.35)$$

Where, for an exponentially falling density distribution as a function of radius $F=1-\tan^2\theta$ [32] and γ is calculated at the resonance.

When comparisons are made with experiments, the results obtained are often presented as iso-signal contours on a $\Delta m^2 - \tan^2(2\theta_v)$ plot. Every solution on the plot corresponds to different scenarios of ν_e propagation through the solar interior. The ‘pre-SNO’ global experimental fit excludes all areas in this parameter space except for four regions (Shown in Figure 2.13). Therefore, the regions on Figure 2.13 are the solutions of the MSW equations

Figure 2.13 : *The pre-SNO combined MSW analysis assuming the Bahcall-Pinsonneault SSM [12]. Shown are the allowed regions (90, 95 and 99 % CL) corresponding to specific MSW solution of ν propagation for active (left panel) neutrinos and hypothetical sterile (right panel) neutrinos which do not participate in the weak interaction. Courtesy C. Peña-Garay*

Solution	δm^2	$\tan^2 \theta_\nu$
LMA	4.2e-5	0.26
SMA	5.2e-6	5.5e-4
LOW	7.6e-8	0.72
VAC	1.4e-10	0.38

Table 2.3 : *The best values for the four MSW solutions which were not excluded before SNO presented its results [37]*

that have not yet been rejected as a solution to the SNP. The best fit values for the MSW solutions are summarized in Table 2.3. The MSW plot is discussed further in Chapter 3 in the context of SNO's latest published results [24, 38].

2.7 The Second Generation of Experiments

2.7.1 Super-Kamiokande

Super-Kamiokande is a second generation upgrade of Kamiokande increasing its mass by a factor of 30. The detector consists of an inner volume used as the detector active volume for identifying neutrinos and an outer volume used for shielding the detector from radioactivity from the rock. The inner detector consists of a 36.2m diameter and 33.8m height, cylindrical volume containing 32 kt of ultra-pure light water. The inner volume is viewed by 11146 photomultipliers providing a 40% photo coverage [7]. Outside this volume and separated by a 0.6m opaque inactive volume is a 2.6m thick volume of light water viewed by 1885 20cm photomultipliers used to identify incoming particles and to shield the inner detector from γ -rays coming from the surrounding rock. The detector fiducial volume amounts to 22.5 kt resulting to a count rate of ~ 10 neutrinos/day. Data acquisition commenced in 1996 with a detector threshold of 6.5 MeV to avoid contamination from low energy backgrounds. In later years, the collaboration reduced their analysis threshold to 5.5 MeV. Energy calibration was done using a

Linac which injects mono-energetic electrons from 5-16 MeV, allowing their energy scale to be known to better than 1%. The Super-Kamiokande collaboration has recently reported a ratio of their measured ^8B neutrino flux compared to the BP2000 SSM [12] of $47 \pm 2.0\%$ [39]. The uncertainty in their measurement (see Table 2.1) is the lowest of any of the neutrino experiments and their result emphasizes the significance of the neutrino deficit.

Chapter 3

SNO: Finding a Solution to the SNP

3.1 The Sudbury Neutrino Observatory

Even with the impressive high statistics data from the first 'Second Generation' experiment Super-Kamiokande, the SNP cannot be considered to be solved. This is because all the neutrino results and in fact, the statement of the existence of a solar neutrino problem, are based on the fact that the results are always compared to the BP SSM. It is clear that to solve the SNP in a definitive way, a model independent experiment must be performed to either refute or accept the notion of neutrino flavor oscillations. This has finally come to fruition with the construction of the Sudbury Neutrino Observatory (SNO), a detector that is not only sensitive to ν_e but is also sensitive to all neutrinos coming from the sun (ν_x). In this way, SNO measures not only the fraction of ν_e compared to the ν_x flux, but also the total number of neutrinos of all flavours coming from the sun. In addition, SNO is able to directly compare this with the BP SSM. This makes SNO unique from other solar neutrino experiments. A diagram of the Sudbury Neutrino Observatory is shown in Figure 3.1.

The Sudbury Neutrino Observatory (SNO) is a real-time water Čerenkov detector to detect solar neutrinos in the range 5 MeV to 14 MeV. SNO consists of a panelled optically clear acrylic

Figure 3.1 : *The SNO detector [40]*

Figure 3.2 : *Layout of the SNO detector [40]*

sphere which houses 1 kt of D₂O (borrowed from the Atomic Energy of Canada Limited), which is the main medium for detecting solar neutrinos. The acrylic sphere is surrounded by a stainless steel geodesic dome on which 9438 Hamamatsu 8 inch PMTs are mounted. The acrylic sphere is embedded in 7 kT of H₂O which is a second medium used for detecting neutrinos and also for shielding the D₂O from background coming from the cavity walls.

The entire SNO detector is optimized to be sensitive to the Čerenkov radiation produced by electrons resulting from neutrino interactions with the active volume of SNO. The SNO detector measures about 8 PMT hits/MeV for an electron traversing the heavy water. The electron vertex, direction and type of neutrino reaction can be determined by using the timing information, location and patterns of the PMT hit distributions (see Figure 3.14 for an example of how the various neutrino reactions are identified).

3.1.1 Neutrino Reactions detected in SNO

Solar neutrinos interact with the active volume of SNO in three different ways, each giving independent information about the solar neutrino flux.

The CC ν Reaction

$$\boxed{\nu_e + d \rightarrow p + p + e^-} \quad (3.1)$$

This reaction occurs for any ν_e exceeding 1.44 MeV and produces an electron which has an angular distribution given by:

$$W(\phi) = 1 - (1/3)\cos(\phi) \quad (3.2)$$

Where ϕ is the angle between the incoming ν_e and the outgoing electron. The angular distribu-

Figure 3.3 : The CC angular distribution expected for $E_\nu=5$ MeV as calculated by NSGK [41]

tion showing the characteristic 2:1 backward-to-forward ratio is shown in Figure 3.3. The total cross-section for the CC reaction has been calculated by many people over the last decade and differs by at most 6%. The most accepted calculation is that of Kubodera *et al.* [42] (known as NSGK calculation), which includes a higher partial wave analysis, including relativistic effects. The total cross-section is plotted in Figure 3.4 in the range of solar neutrino energies for the NSGK calculation. This has been updated [43] and accounts for a 1% change in the cross section from reference [42].

From the kinematics of the CC reaction, the outgoing electron has an energy spectrum given by:

$$T_e = E_{\nu_e} - Q - \frac{P^2}{m_p} - \frac{(P_e - P_{\nu_e})^2}{(4m_p)} \quad (3.3)$$

Where the P_e and P_{ν_e} are the electron and neutrino 3-momentum and P is the relative momentum of the two protons. J. N. Bahcall comments [44] that the last two terms are often neglected in the literature and account for the fact that there is no one-to-one correspondence between incident neutrino energy and consequent electron recoil. This is shown in Figure 3.5 where

Figure 3.4 : *The CC total cross-section as calculated by NSGK [41]. Data taken from K. Kubodera's website [41]*

Figure 3.5 : *The CC electron recoil energy spectrum for $E_\nu=5$ MeV and $E_\nu=7$ MeV. Data taken from K. Kubodera's website [41]*

the differential cross-section is plotted for various recoiling electron energies for an incident neutrino energy of 5 and 7 MeV. The recoil energies of the electron are further smeared by the inclusion of the detector resolution.

Detection of the CC reaction is facilitated by the Čerenkov radiation produced by the electron leaving the vertex which is explained in a later section. This reaction is also sensitive to the high flux ν_e emission in the first 0.1s after stellar collapse, signalling the occurrence of a supernova. The SSM predicted rate for solar ν_e 's interacting via the CC reaction is approximately 6 events/day.

The ES ν Reaction

$$\boxed{\nu + e^- \rightarrow \nu + e^-} \quad (3.4)$$

This reaction is sensitive to all neutrino types ¹ and is the main detection reaction used by previous solar ν detectors, such as Super-Kamiokande. The differential cross-section for $\nu_e - e^-$ elastic scattering is derived by considering the Feynman diagram for W and Z exchange in the t-channel and given by:

$$\frac{d\sigma}{dT} = \sigma_e [g_{L_e}^2 + g_R^2 (1 - T/E_\nu)^2 - g_{L_e} g_R (T/E_\nu^2)] \quad (3.5)$$

where T is the kinetic energy of the recoil electron, $\sigma_e = 88.083 \times 10^{-46} \text{ cm}^2$, $g_{L_e} = \frac{1}{2} + \sin^2 \theta_w$ and $g_R = \sin^2 \theta_w$. The differential cross-section for $\nu_x - e^-$ is less because the W-exchange channel is not available for the non-electron flavours. In this case, the differential cross-section should be modified so that for the formula above g_{L_e} is replaced with $g_{L_e} - 1$. The total cross-section for elastic scattering convolved with the ^8B neutrino shape for both the ν_e and ν_x electron elastic scattering is shown in Figure 3.6 as a function of the minimum recoil kinetic energy T_{min} .

One important feature of the ES scattering reaction is that the recoil electron is strongly forward peaked and if one looks at the scattering angle of the outgoing electron to the incoming neutrino coming from the sun ($\cos \theta_\odot$), there is a cut-off angle ($\cos \theta_\odot|_{min}$) corresponding to the detector threshold. The minimum $\cos \theta_\odot$ is given by:

$$(\cos \theta_\odot|_{min})^2 = \frac{T(1 + E_\nu)^2}{(T + 2)E_\nu} \quad (3.6)$$

The angular distribution for the outgoing electron for incident neutrino energies of $E_\nu = 5$ and $E_\nu = 8$ MeV is shown in Figure 3.7. From Figure 3.7, it is seen that the recoil electron gives much directional information and in fact this reaction was used by the first Kamiokande experiment to confirm that ν 's are emitted from the sun. This reaction is detected by observing

¹The NC and ES reactions are sensitive to ν_x and ν_e but not the hypothetical sterile ν_s which do not participate in left-handed currents.

Figure 3.6 : The total cross section for both ν_e (solid) and ν_x (dotted) elastic scattering ($x=\mu$ or $x=\tau$). Data taken from [15]

Figure 3.7 : The ES angular distribution expected for $E_\nu=5$ and 8 MeV for a detector threshold of kinetic energy 3 MeV. Also shown are the corresponding minimum $\cos\theta_\odot$. Data taken from [15]

Figure 3.8 : The total cross section in cm^2 for the $\nu + d \rightarrow n + p + \nu$ NC reaction as a function of neutrino kinetic energy. Data taken from [41]

the Čerenkov radiation produced by the forward going electron. The Standard Solar Model predicts 3 detectable ES neutrino reactions per day.

The NC ν Reaction

$$\boxed{d + \nu \rightarrow p + n + \nu} \quad (3.7)$$

This reaction is completely flavour blind and so is sensitive to all types of ν 's. It is the reaction that is unique to SNO, in that the rates measured by this reaction can be directly compared to the rates observed by the CC reaction and confirm flavour conversion independent of astrophysical models. The accepted total cross-section as calculated by Kubodera *et al.* (NGSK calculation) [43] is shown in Figure 3.8. The theoretical uncertainty in the NSGK calculation is expected to be $\sim 1\%$ for the ratio of the CC and NC reactions.

The detection technique for this reaction is more complex than the other reactions and de-

serves further explanation. The proton emitted from the vertex is immediately stopped without producing any Čerenkov light or scintillation light. Consequently, the only reaction product that is detected is the neutron. Since D_2O is such a good moderator, the neutron rapidly loses energy through scattering. On average, the neutron will travel 14 cm before coming to thermal equilibrium with its surroundings. Subsequently, the neutron scatters at random and may be absorbed by the D_2O or other additives, such as NaCl. Upon capture onto the Cl atom, high energy γ -rays are released. These Compton scatter and produce electrons, which in turn emit Čerenkov radiation and are detected. The SNO detector response to neutrons is a Gaussian peaking at ~ 5.5 MeV with a 1σ width of approximately 1.5 MeV, and is known as the “neutron peak”.

Simple Monte Carlo calculations show that the neutron capture process can be understood only by assuming a uniform distribution of ν events in SNO and the fact that the neutron thermalizes and starts a random walk. The capture efficiency calculated by this method and other more sophisticated calculations [45] predicts about 83% capture efficiency for 2 tonne NaCl dissolved in the D_2O .

A second NC detection method will be starting in January 2003 involving discrete charged particle counters that are distributed throughout the D_2O active volume. The difficulty is that a balance must be obtained between high capture efficiency and the blocking of the Čerenkov light by the counters. These effects have been optimized in a design utilizing several hundred 3He proportional counters suspended along 109 strings, anchored along the bottom of the acrylic vessel. The counters utilize the high 3He neutron capture cross section of 5330 b. This allows these counters to be placed sparsely through the D_2O active volume, so that the Čerenkov light produced by other reactions is not impeded. One of the disadvantages with this method is that radioactive contamination in the counter materials produces beta and α -particle particles in the counter. Investigation of this contamination has concluded that these events can be separated from neutron capture events by pulse shape discrimination. The capture efficiency

for this method is expected to be much less than the dissolved salt technique by about 45%. The Standard Model predicts 30 neutrino NC interactions per day in SNO.

A significant background to the NC reaction is any γ -ray that has an energy exceeding 2.223 MeV, so that it may photo-disintegrate a deuteron and produce a free neutron. These backgrounds are “perfectly disguised” since we cannot distinguish free neutrons created by the neutral current interaction from a free neutron produced by a high energy γ -ray. These neutrons will contribute to the neutron peak produced by the NC interaction. These backgrounds are further discussed in Chapter 4.

3.1.2 Detection of Neutrino Reactions

The observable reaction products for the charged current and elastic scattering are the recoil electrons. These electrons are observed by detecting the Čerenkov photons produced while the electron exceeds the speed of light in D_2O . Čerenkov photons are emitted in a cone pointing in the direction of the electron with an opening angle defined by $\cos\theta = \frac{1}{\beta n}$, where β is the relativistic beta and n is the refractive index. The expression for the number of Čerenkov photons radiated over an electron path length dx and are detected by the PMTs is given by:

$$\frac{dN}{dx} = 2\pi\alpha \int \left(1 - \frac{1}{\beta^2 n^2}\right) \epsilon_c(\lambda) \frac{S(\lambda)}{\lambda^2} d\lambda \quad (3.8)$$

$$\alpha = 1/137$$

$$\lambda = \text{wavelength of photons in response range of PMTs}$$

$$\epsilon_c(\lambda) = \text{photocoverage efficiency}$$

$$S(\lambda) = \text{Normalized PMT photocathode response}$$

$$n = \text{Index of refraction}$$

The Čerenkov photons produced by the recoiling electron are then detected by the PMTs

surrounding the acrylic vessel. SNO defines the number of photons that hit the photocathode and produces a measurable signal within 100 ns time window as the number of 'PMT Hits' or 'NHIT'. As is shown in the next paragraph the number of 'PMT Hits' can be thought of as being approximately proportional to the energy of the electron that has produced the Čerenkov photons. This fact allows it to be used as a neutrino energy estimator.

Analytic Calculation of Number of PMT Hits for Mono-energetic Electrons

The number of PMT Hits can be calculated analytically by determining the number of Čerenkov photons that are created until the electron loses so much energy that $\beta < 1/n$. The energy corresponding to the case when $\beta = 1/n$ is known as the Čerenkov threshold energy of the medium. The number of photons is then scaled by various detector related efficiencies as described in the previous section. In this prescription the expression for the number of PMT hits is given by [46]:

$$HITS = \int_{E_{thr}}^E \left(\frac{dN}{dx} \right) / \left(\frac{dE}{dx} \right) \epsilon dE \quad (3.9)$$

Where, $\left(\frac{dN}{dx} \right)$ is the number of Čerenkov photons created per path length dx , $\left(\frac{dE}{dx} \right)$ is the Bethe-Bloch energy loss for e^- 's per path length dx and the expression is integrated from the initial energy of the electron to the Čerenkov threshold energy (E_{thr}). The efficiency ϵ is the product of the photo-coverage efficiency (assumed to be 65% [8]) and the probability of photon absorption in the D_2O and H_2O . The probability of photon absorption was calculated in a separate Monte Carlo calculation where isotropic scattering and a 40 m absorption and scattering mean free paths were assumed. The calculation does not take into account optical effects at the D_2O /Acrylic Vessel interface. However, since the mono-energetic electron starts from the center, the Čerenkov photons will be incident normally to the surface, thus reflection and refraction are neglected in this calculation. Furthermore, multiple scattering is neglected since the energy loss is the same in any direction, and is not expected to impact significantly on the number of

Figure 3.9 : *The number of PMT hits as a function of electron energy for the analytic calculation described in the text (solid) and a SNOMAN Monte Carlo (dotted).*

photons detected. The result of this calculation is shown in Figure 3.9 where the number of PMT hits are plotted as a function of electron energy for mono-energetic electrons that start from the center of the D_2O . Here it is seen that the number of PMT hits are proportional to the energy of the recoil electron, making the number of PMT hits an observable for determining the energy of the electron. The number of PMT hits is approximately 11 hits/MeV. Shown in Figure 3.9 is the prediction based on calculations with the SNOMAN Monte Carlo. SNOMAN is the main SNO Monte Carlo and Analysis code to be described later. The SNOMAN Monte Carlo properly takes into account the transport of the electrons and γ -rays, the optical effects of the various detector components and other efficiencies. The SNOMAN predicted calibration of the number of PMT hits to electron energy is approximately 8 hits/MeV. While the analytic calculation does not predict the correct number of PMT hits/MeV, it does predict a linear relationship of electron energy to the number of PMT hits.

The response to γ -rays is different since γ -rays do not produce Čerenkov light. It is only when the γ -ray Compton scatters or pair produces electrons that exceed the Čerenkov threshold

Figure 3.10 : *The number of PMT hits for a 7 MeV electron (solid) and 7 MeV γ -ray (dotted) as calculated by the SNOMAN Monte Carlo*

energy that the γ -ray leads to the radiation of Čerenkov light. However, the initial energy of the gamma is shared among several electrons created and these electrons only emit Čerenkov photons as long as the Čerenkov condition is satisfied. Therefore, electrons and γ -rays of identical energies produce different number of PMT hits. A comparison of the number of PMT hits for a 7 MeV γ -ray and electron is shown in Figure 3.10.

It should be mentioned that PMT hits alone as an energy estimator is not satisfactory because hit PMTs must be corrected for the PMT noise and detector related efficiencies to make it a useful parameter to determine the energy of the recoiling electron.

3.2 Detailed Description of the Sudbury Neutrino Observatory

An important design criteria for any solar neutrino detector is the reduction of the natural background present. The two main backgrounds for all solar neutrino detectors are cosmic

ray muons producing spallation products, and the low energy background coming from the decay of ^{232}Th and ^{238}U present in the materials out of which the detector was constructed. With the Sudbury neutrino observatory ², this has meant that the detector was built very deep underground to decrease the muon flux in the detector. The SNO detector is located in a large 34 m high, 22 m in diameter, barrel shaped cavity excavated at the 6800 ft level in INCO Ltd's Creighton mine near Sudbury, Ontario. To reduce the low energy background, very strict cleanliness protocol had to be implemented both for the maintenance of the detector as well as the choice of materials out of which the detector is constructed. The main detector site is supported by numerous accompanying halls and rooms. Upon entry to the laboratory, an individual passes through a series of rooms, each having increasing level of cleanliness ³. A figure showing the layout of the detector site is shown in Figure 3.2. Each individual detector component starting from the center of the detector and proceeding radially outward and are described in the next section.

3.2.1 The D₂O Active Volume

SNO employs as its main active volume 1kt of 99.91% isotopically pure D₂O. The D₂O was brought underground in specially designed rail-cars in 6 tonne increments. The D₂O system consists of 2 independent circuits, a receiving line and a recirculation loop.

Receiving Line

The first element in the receiving line is a set of ion exchange columns where the water is stripped of its ionic contents, especially Potassium ⁴. It is important to purify the D₂O as early

²This section and the following sections are adapted from [40] and [47].

³The cleanliness protocol for the individual requires the taking of a shower, change into completely clean clothes and the passing through an airshower. This is a requirement for entry into the laboratory.

⁴Non-negligible amounts of K were found to be in the D₂O when it was received. It has been assumed that this is due to prior treatment with KMnO₄

as possible to prevent any plating out of these elements on the subsequent piping. For this reason filters coated with DTiO are used immediately after the ion-exchange columns followed by 0.03 micron filters which will prevent DTiO fines from reaching the detector. Finally, the processed D₂O was stored in a 60 tonne polypropylene-lined tank until the D₂O was inserted into the acrylic vessel.

Recirculation Loop

The second requirement of the D₂O system is to re-purify and cool the the D₂O after it has been in the acrylic vessel for a certain time. This is accomplished by first sending the D₂O from the acrylic vessel through 2 large (550 cm long by 22 cm diameter) specially designed reverse osmosis(RO) units constructed entirely out of Hastalloy ⁵. The concentrate stream containing residual radioactive ions are passed through adsorption columns containing MnO_x beads to further reduce the Th, Ra and Pb concentrations. The D₂O is then passed through an ultra-filtration unit to prevent MnO_x fines from passing into the acrylic vessel ⁶. The next stage in the recirculation loop is a process degasser used to extract the Rn present in the D₂O and a final heat-exchanger to cool it to approximately 8°C.

3.2.2 The Acrylic Vessel

The D₂O itself is housed in a 5.5 cm thick optically transparent 12 m diameter acrylic vessel. The vessel is composed of 122 UVT (ultraviolet transmitting) acrylic tiles which match closely the PMT spectral response. At the time of construction each acrylic panel was bonded together using a specially formulated epoxy manufactured by Reynolds Polymer Technology that cures at room temperature. The vessel includes a 6.8 m long and 1.5 m diameter chimney connecting

⁵Hastelloy is a trademark for a series of high-strength, nickel based, corrosion resistant alloys

⁶While at Carleton University I was involved in several investigations in determining the magnitude and implications of the MnO_x fines [48], [49]

the top of the acrylic vessel to the deck. This allows direct access to the D_2O volume necessary for the deployment of calibration sources. The entire acrylic vessel is suspended from the deck by vectran ropes. The ropes were attached along the equator to special acrylic panels with grooves for the ropes. The tension on each of the ropes is constantly being monitored.

The H_2O Shielding

The AV is itself immersed in 7300 tons of ultra-pure H_2O . The H_2O surrounding the acrylic vessel shields the D_2O from backgrounds coming from the walls of the cavity, and provides a positive buoyancy to the acrylic vessel minimizing the tension on the AV suspension ropes. The most important criteria of the light water as with all SNO detector components is its inherent high radio-purity. This was accomplished using a dedicated purification system converting potable mine water to ultra-pure water.

Receiving Line

Incoming potable water contains sand, bacteria, algae, inorganic salts, organic molecules and gases. After the water has fallen 2.2 km, the water is super-saturated with air, and the first stage of the receiving line is the de-aerator tank where some of the O_2 and N_2 are removed. The water then passes through a multi-media filter consisting of a bed of sand and charcoal to remove large particles, followed by a 10 micron filter to remove smaller particles. The water is then softened using zeolite softeners, removing iron and exchanging ions, such as Ca and Mg, for Na atoms. The next stage is a reverse osmosis system reducing the inorganic salt levels by a factor of 20 and large particles with high efficiency. The rest of the receiving line is the same as the recirculation loop and described in the next section.

Recirculation Loop

The water from the cavity and the water from the last purification stage when the water is received, pass through ion-exchange columns. The next element is the UV unit used to eliminate residual biological activity. The light water is degassed using a custom built process degasser reducing the dissolved gasses, such as O₂, N₂ and Rn in the water. The water is passed through a unit exposing the water to 254 nm UV light killing biological activity. When the detector was commissioned, it was found that the degassed water was causing the gas present in the PMT connectors to diffuse out of the connector leading to breakdown ⁷. It should be noted that an essential step for any light water entering the cavity is the re-saturating the water with nitrogen. Finally, a chiller cools the water to 10°C before the water is returned to the cavity.

The light water volume is divided into two sections: the light water between the cavity, and the photomultiplier support structure (PSUP), and the water between the acrylic vessel and the AV. These two waters are separated by a thin plastic barrier at the PSUP which prevents mixing of the much dirtier (exposed to the PMT cabling, cavity liner, large surface of the PSUP) outer water than the light water between the AV and the PSUP.

3.2.3 Cover Gas System

A potential background, particularly Rn which is present in laboratory air at a concentration of 3 pCi/L, occurs when there is a large increase in air pressure outside the detector water volumes. A nitrogen cover gas system has been designed that functions as a barrier between the water and the laboratory air.

⁷At Carleton University I was a member of a task force to determine the cause of the problem. Investigations included long-term studies of 6 SNO PMT bases under high pressures and testing possible changes to the PMT connectors.

3.2.4 PMTs and PSUP

Surrounding the acrylic vessel are 9400 Hamamatsu Photonics (modified R1408 PMTs) 8 inch diameter photomultiplier tubes. Schott Glaswerke was commissioned to produce a custom made PMT glass having a low inherent radioactivity (40 ppb Th and U) and a high transmission at low wavelengths. Additional properties of the PMTs are very fast transit times (30 ns) and narrow transit time spread (1.6 ns) allowing very precise measurement of the time that the PMT fired aiding in vertex reconstruction. Also mounted on the PSUP are 90 outward looking tubes (OWL's) which act as an anti-coincidence shield against muons and spallation events. In addition to the 9400 inward looking PMTs and the OWL's there are 50 "low-gain" PMTS with a dynamic range 2 orders of magnitude higher than regular PMTs. These PMTs allow particularly bright events to be studied. Each PMT (except the OWL PMTs) is surrounded by a reflector made out of Omega aluminum which not only increases the photocathode coverage to approximately 64%, but also protects PMTs from the light caused by radioactive decay in neighbouring PMTs. The PMTs are placed onto hexagonal ABS panels and mounted onto sides of a steel geodesic icosahedron that make-up the PSUP. The PMTs are connected by a 32 m long RG59/U cable providing the high voltage (HV) to the PMTs and carrying the signals to the SNO electronics.

3.2.5 The SNO Cavity

Imbedded in the walls of the cavity has is an array of magnetic field compensation coils that reduce the magnetic field so that the effect of the earths magnetic field on the PMTs is negligible. In addition, the cavity is fitted with a urylon liner which acts as a barrier against Rn coming from the rock.

3.2.6 The Electronics and Data Acquisition

The main requirement of the SNO electronics is to be able to provide nanosecond time and charge measurements of the PMTs with minimum deadtime for:

- Continuous trigger rates up to 300Hz as expected from routine calibrations
- Large bursts of data exceeding kHz for a short time period as expected from a supernova.

These two requirements mean that the SNO detector must have a very large dynamic range, allowing hardware buffering for large bursts of data.

The SNO electronics is essentially divided into 3 streams: the PMT stream, the trigger system and the event recording stream. Each is discussed separately below. The PMT stream is the stream of data consisting of the charges of the individual PMTs. The PMT stream can be seen as INPUT into the master trigger card which decides whether it should OUTPUT a global trigger (GT) to initiate the reading of the time and charge information from all of the PMTs. At this point all the information is read from the PMTs and built into an event. Each stream is summarized in the next few sections. Refer to Figure 3.11 for a summary of the SNO electronics and data stream.

PMT Stream

Once Čerenkov light has hit the PMT, the PMT pulse travels up the 32 m long cable to the PMT interface card (PMTIC). The purpose of the each PMTIC is to supply HV and to deliver the signal to the Front End Card(FEC) which processes the PMT signals for 32 channels. The FEC is composed of 4 daughterboards (serving 8 channels each) containing 2 CMOS chips, the SNOD and SNOINT chips, which do a variety of tasks when a PMT signal arrives. The function of the SNOD chip is to fire a discriminator pulse if the PMT amplitude exceeds the discriminator threshold, start an internal TAC and send a logic pulse to the Master Trigger Card (MTC). This is the INPUT signal to the MTC to start the decision making process of

Figure 3.11 : *Summary of SNO data stream*

whether a GT should be sent out to all the PMTs to read the charges. Next, the signal travels to the SNOINT chip which makes 3 charge measurements:

- **QLOSHORT**= Charge is measured for a time period consistent with direct light for charges having a range of 1/30 photoelectron to 100 photoelectrons.
- **QHISHORT**=Charge is measured for a time period consistent with direct light for charges up to 1200 photoelectrons
- **QLOLONG**=Charge is measured for a longer time period (~ 200 ns) to include late light from reflections.

If a GT issued by the MTC does not arrive within 400ns of the start of the TAC ramp, the system resets itself and allow the charges and times of a new PMT hit to be stored.

Trigger Stream

As mentioned when a PMT pulse arrives at the FEC and exceeds a prescribed discriminator threshold, a logic signal is sent to the MTC to inform it that a PMT hit has occurred [50]. A global sum is performed every 20 or 100 ns's of all the PMTs, and compared to a prescribed amplitude which usually corresponds to the sum of logic pulses of 17 PMTs. If the amplitude exceeds this amplitude, a global trigger (GT) is issued. This is the standard way the SNO detector is triggered for neutrino data.

Once a GT is fired, a logic pulse is sent back to all the FEC's to stop the TAC and initiate the storing of the 3 charge measurements and the 1 time measurement. The GT also increments a global trigger number (GTID) which associates a number with the GT and synchronizes it with a 50 MHz clock, and an event time.

In addition, to the default method of triggering, provision is made for asynchronous triggering used for triggered calibration sources. This is important for the Proportional Calibration

Source described in preceding chapters ⁸. Essentially a logic signal from the calibration source is sent into an *OR* of the central trigger system, and a GT is issued immediately. This allows the signal from the calibration source to be isolated from other backgrounds which may occur during a calibration run.

Event Building Stream

Once a GT has arrived at the FEC and has issued the command that the three charges and one time measurement should be stored, a logic signal is sent to a sequencer in order to inform it that data is available to be read. At the sequencer's convenience the FEC's memory is read and sent to Analog-to-Digital Converters (ADC) that convert the 3 analog charges and time to a digital word. These signals are stored in a 4MB local FEC memory which operates on a First-In-First-Out basis and allows a large number of events to be buffered in case a supernova occurs. The PMT data is written to three 32-bit data words (known as the 'PMT bundle') containing information about the geographical location of the PMT, the 3 charges and time, the GTID that the event is associated with and other diagnostic information. The DAQ computers can now read out the 'PMT Bundle' and along with information of all the other PMTs build it into an event. The DAQ computer then writes the data to disc as a ZDAB file, which is a ZEBRA based file format used by the SNO collaboration.

3.2.7 The SNOMAN Monte Carlo

SNOMAN is the dedicated SNO Monte Carlo and analysis code which has been written by the SNO collaboration to analyze the physics in the SNO detector and to simulate calibration sources deployed in the active volume. More details on SNOMAN and how calibration geom-

⁸As will be described in Chapter 6, the PCS engineering run was a run where one of the external asynchronous triggers (EXT4) was utilized.

etry's are simulated are provided in Chapter 6. The code relies on the EGS4 [51] code system to simulate beta particles and γ -rays, GEANT [52] for muons and MCNP [53] for the propagation of neutrons. SNOMAN uses CERN's ZEBRA [54] code to overcome FORTRAN's lack of memory management. SNOMAN was written in a modular way in the sense that every processor communicates to a central data structure and each is decoupled from other processors. In this way, it is easy to add additional processors, such as new fitters. SNOMAN also uses a database program interfaced to CERN's HEPDB [55], containing calibration constants, data cut banks and banks which describe the general health of the detector.

3.3 Calibration of SNO

Calibration sources are used to relate the PMT times and charges to the neutrino vertex and to tune the SNOMAN monte carlo. These sources aim to understand the SNO detector response to electrons, γ -rays, Cerenkov photons and neutrons, occurring throughout the active volume of SNO. The various calibration sources also help test various fitters and reconstruction algorithms as well as determine the efficiency of various data cuts to the neutrino data.

Calibration sources are deployed throughout the SNO active volume using a manipulator system. The manipulator consists of a stepping motor that lowers calibration sources by a central rope from the deck to various places in the D₂O or through vertical tubes between the AV and the PSUP called 'guide tubes'. The source is first placed into the glove box (an airtight enclosure where the sources are handled) or source tube ⁹. The source is then lowered into the D₂O or guide tubes. The guide tubes only allow the calibration sources to be deployed along the vertical axis. To determine the off-vertical axis response of various calibration sources in the D₂O side ropes are used. Side ropes are the ropes that run through pulleys connected to several

⁹The glove box and source tube are part of a large component called the umbilical retrieval mechanism (URM) located in a separate clean room on the deck called the Deck Clean Room (DCR).

points on opposite sides of the AV. Each rope has a separate stepper motor, and by adjusting the tension the calibration source can be deployed in 3/4 of the area of a plane. The sources can be deployed in two separate orthogonal planes intersecting in a line that runs vertically through the center of the detector. In addition to the central rope and the side ropes, the source is also connected to an umbilical. The umbilical is a source specific cable that has all the necessary electrical/gas/fiber optic connections for each source. The umbilical also provides an extra support should the ropes fail, since umbilicals can support the full weight of the calibration source. The manipulator system is shown in Figure 3.12.

3.3.1 Optical Response

To determine the optical properties of the detector, such as the attenuation length, scattering length and absorption length of the D_2O and H_2O , a N_2 laser connected to a diffuser ball is used [56]. The laser generates monochromatic pulses of light, tunable from 337 nm to 370 nm. By deploying the laser ball at various positions, distances and angles from the PMTs in the detector, the attenuation length of the D_2O and angular response of the PMTs can be determined. The scattering can be understood by looking at the timing histogram of the PMTs [57]. For example, one can recognize structure in the PMT timing histogram corresponding to reflections from the AV and other components and from Rayleigh scattering.

3.3.2 Energy Response

There are a set of calibration sources which aim to understand the SNO detector energy response. The most important of these sources is the ^{16}N tagged γ -ray source [58, 59]. This source is produced by using a D-T neutron generator to activate oxygen and produce ^{16}N . ^{16}N beta decays with a half-life of 7 s to emit 68% of the time a 6.1 MeV gamma. This calibration source can be tagged by using a scintillator/PMT arrangement to detect the beta which accom-

Figure 3.12 : *The manipulator system used in SNO to deploy calibration sources*

panies the 6.1 MeV gamma. This is the main source used for determining the detector energy scale, uncertainty and drift in energy scale over time.

Other calibration sources used to determine the SNO detector response at higher energies are:

1. **^8Li Source:** Beta spectrum with endpoint 13.1 MeV is produced by neutron activation on ^7Li [60], [61]
2. **p-T Source:** 19.8 MeV gamma is produced by proton capture on Tritium [62], [63].

3.3.3 Neutron Response

SNO uses acrylic encapsulated ^{252}Cf sources to calibrate the NC reaction [64]. ^{252}Cf spontaneously fissions and produces many free neutrons which are thermalized in the D_2O and readily captured on D, H or Cl. This source exactly calibrates the NC, since a free neutron results from a NC reaction. Various triggered neutron sources are being constructed, but at the moment it is not clear whether they are necessary.

3.3.4 Low Energy Response

Various low energy calibration sources have been used by SNO to calibrate the SNO detector response to natural radioactivity that is present in trace amounts in the D_2O and H_2O . These sources [65] are essentially blocks of acrylic with a small amount of ^{228}Th and ^{238}U placed in the middle. The sources have allowed the SNO detector to make very precise measurements of the NC and CC, and have aided in solving the SNP as described in the next section, although they do suffer from some problems. The first problem with these sources is that in an effort to ensure that no Th/U will escape the acrylic, the acrylic is made exceedingly thick consequently the Čerenkov light produced by the $\beta - \gamma$ cascade is produced in the acrylic, not the D_2O .

The second significant problem is that the calibration sources are not triggered allowing other backgrounds that occur during the deployment to contaminate the data, as well as the neutrons resulting from gamma photodisintegration of the deuteron. For these reasons, a next generation calibration source has been developed to overcome these difficulties. This calibration source, known as the Proportional Counter calibration Source (PCS), is the subject of this thesis, and its motivations for deployment, design, quality control and assurance, simulation and data analysis are described in the following chapters.

However, during my time working on the development of the PCS, SNO has made several very important measurements which should be discussed in the historical context of the previous chapter. Therefore, in the next section SNO's results in measuring the CC and NC fluxes and its implications for solving the SNP are described. The remaining chapters will return to the main subject of the thesis, which is the PCS as a method of calibrating the low energy background in SNO.

3.4 SNO and the Solution to the Solar Neutrino Problem

The previous chapter introduced the notion of matter enhanced neutrino oscillations as a solution to the SNP. The chapter described a range of solar neutrino detectors which all suggest a deficit of solar neutrinos, but do so, only when the solar neutrino flux is compared to the flux expected from the SSM. The present chapter describes the measurements SNO¹⁰ can make as a means to solve the SNP in a model independent way. This is because SNO can measure both the flux of ν_e by measuring the CC, but can also measure the total flux of active solar neutrinos coming from the sun through the NC. The fact that SNO can make a measurement of the total active solar neutrino flux, makes SNO unique among other solar neutrino detectors.

In April 2002, the SNO collaboration published [24, 38] results for the observed rates for

¹⁰Much of the information presented in this section comes from [24] and [38]

all three (CC,NC,ES) neutrino reactions. In the sections to follow, the steps in the analysis and the results are briefly summarized.

The Neutrino Data Set

The solar neutrino data consists of 306 live-days of data taken between November 1999 and May 2001. During this time, the detector configuration was frozen ¹¹ and the detector had as its sensitive volume pure D₂O. As mentioned in the next chapter, the SNO detector suffers from many types of background, both natural (radioactive backgrounds inherent in the detector components (LEB)) and instrumental. The first step in the analysis is to characterize the instrumental backgrounds, apply cuts to remove them and ascertain the effect of the cuts on the neutrino data [66]. The next step in the analysis is to determine the contamination of the data set due to the decay of natural thorium and uranium in the detector components. Several techniques have been designed to do this and are described in more detail in the next chapter. The techniques are divided in two groups: the *In-Situ* techniques which utilize the PMT hit patterns to characterize the various backgrounds and the *Ex-Situ* radiochemical techniques. A summary of the results for the determination of the concentration of ²³²Th and ²³⁸U is shown in Figure 3.13. The levels determined by the *In Situ* and *Ex Situ* techniques lead to a LEB contamination of 45^{+18}_{-12} events in the neutrino data set.

An important consequence of the LEB, as has been discussed earlier, is that some of the γ -rays produced may photo-disintegrate the deuteron in the D₂O and produce a free neutron. This means that the analysis must also calculate the number of free neutrons produced. This was done by using ²⁵²Cf neutron calibration sources to determine the SNO detector response to free neutrons and the neutron capture efficiency as a function of radius. The average rate of free neutron production due to backgrounds in the D₂O is determined to be 1.0 ± 0.2 neutrons per

¹¹The voltages on all the PMTs were not varied. Every attempt was made to ensure a constant detector response during the time of running

Figure 3.13 : Thorium (a) and uranium (b) backgrounds (equivalent equilibrium concentrations) in the D₂O deduced by in situ and ex situ techniques (described in the next chapter). The MnOx and HTiO radiochemical assay results, the Rn assay results and the in situ Cherenkov signal determination of the backgrounds are presented for the period of this analysis on the left-hand side of frames (a) and (b). The right-hand side shows time-integrated averages including an additional sampling systematic uncertainty for the ex situ measurement.

day and $1.3^{+0.4}_{-0.5}$ neutrons per day from backgrounds external to the AV. Other sources of free neutrons, such as those coming from spallation from cosmic rays and atmospheric neutrinos are rejected using software cuts [66]. The total neutron background contaminating the neutrino data set during the period of data taking is 78 ± 12 neutrons.

Finally, the cleaned neutrino data constituting of the sum of the CC, NC and ES events amount to 2928 neutrino events. For each neutrino event the variables available are the reconstructed position and direction and the number of PMT hits (NHITS) the event has triggered. The number of PMT hits due to the event can be converted into an estimation of the kinetic energy of the neutrino (T_{eff}) using the RSP processor [67] available in SNOMAN. The RSP processor uses the prompt PMT hits and corrects it for the knowledge of the number of live PMT tubes and the optical response of the PMTs. The processor then assigns an energy to the event as calibrated with the ^{16}N 6.1 MeV gamma source. From the reconstructed position and directional information, the data is divided into bins of $\cos(\theta_\odot)$ (where $\theta_\odot$ is the angle the fitted direction makes with the sun) and in R^3 (in units of AV radii). A further $R=0.92$ fiducial cut and $T_{eff} > 5.0$ MeV cut is applied to produce the final neutrino analysis data set. The data set binned in terms of $\cos(\theta_\odot)$, R^3 and T_{eff} are shown in Figures 3.14.

Signal Extraction

To test whether there are only electron neutrinos coming from the sun, probability density functions ¹² (PDF's) were generated using the SNOMAN Monte Carlo for each of the event observables. This hypothesis assumed no neutrino oscillation distortion of the ^8B shape. Included in the signal extraction are PDF's associated with the LEB. The extended maximum likelihood method was used to separate the data set containing the sum of all the neutrino reactions into the contribution of each specific neutrino reaction. Each neutrino reaction has a specific distribution in terms of the variables $\cos(\theta_\odot)$, R^3 and T_{eff} . For example, the ES reaction produces highly directional neutrinos pointing away from the sun and this is used in the analysis to determine the contribution of the ES to the total neutrino data set. The contributions

¹²The probability density function of a continuous random variable x is a function such that $P(a < x < b) = \int_a^b f(x)dx$ where $\int_{-\infty}^{+\infty} f(x)dx = 1$. For a discrete distribution the integral becomes a sum over bins, with the requirement that the sum over all bins is unity

Figure 3.14 : *a) Distribution of $\cos(\theta_{\odot})$ for $R < 550$ cm. b) Distribution of the volume weighted radial variable R^3 in terms of AV radii. c) Kinetic energy for $R < 550$ cm. Also shown are the Monte Carlo predictions for CC, ES and NC + background neutron events scaled to the fit results and the calculated spectrum of LEB events. The dashed lines represent the summed components and the bands show the $\pm\sigma$ uncertainties. All distributions are for events with $T_{eff} > 5.0$ MeV.*

Flux description	Value in $10^6 \text{ cm}^{-2} \text{ s}^{-1}$
Φ_{CC}^{SNO}	$1.76^{+0.06}_{-0.05}(\text{Stat}) \pm 0.09(\text{syst.})$
Φ_{ES}^{SNO}	$2.46^{+0.24}_{-0.23}(\text{Stat}) \pm 0.12(\text{syst.})$
Φ_{NC}^{SNO}	$5.08^{+0.44}_{-0.43}(\text{Stat})^{+.46}_{.43}(\text{syst.})$
Φ_e	$1.76 \pm 0.05(\text{Stat}) \pm 0.09(\text{syst.})$
$\Phi_{\mu\tau}$	$3.41 \pm 0.45(\text{Stat})^{+0.45}_{-0.48}(\text{syst.})$

Table 3.1 : *The extracted fluxes for the 3 neutrino reactions and the flavour components to which the neutrino reaction fluxes correspond [38].*

of each neutrino reaction to the total as determined using the extended maximum likelihood method is shown in Table 3.1.

All the fluxes presented in Table 3.1 are presented under the hypothesis that only ν_e 's are present in the solar neutrino flux. A change of variables can be made to present the extracted neutrino reaction fluxes in terms of their weak flavor content. The extracted flavor neutrino fluxes is also shown in Table 3.1.

Physics Interpretation

A quick glance at Table 3.1 reveals that the CC flux is not identical to the NC flux, as would be evident in the no neutrino flavor oscillations scenario (i.e. no distortion of the ^8B shape). In fact, the $\Phi^{\mu\tau}$ is greater than 5.3σ away from 0. This is shown in Figure 3.15 where the neutrino fluxes are plotted in terms of the neutrino flavour components. The data bands represent the one σ measurements of the 3 neutrino reaction fluxes. The bands intersect at the fit values of the electron and non-electron neutrino components of the neutrino flux. From the diagram, it is also evident that the fitted flavor fluxes are consistent with the SSM expectation. Thus, not only has SNO decomposed the observed neutrino flux into an electron and non-electron neutrino component, but SNO also has strong evidence that the sum of all the neutrino flavors is consistent with the SSM.

Some solar neutrino oscillation scenarios predict that the neutrino energy spectrum (and

Figure 3.15 : Flux of 8B solar neutrinos plotted in terms of their electron and non-electron flavor components for all 2 solar neutrino reactions. Also shown are the SNO total neutrino flux measurement (solid band) and the SSM prediction (dashed lines) [38].

thus the individual neutrino fluxes) differ during the night and day. This is due to the regeneration of neutrinos through the earth predicted by some MSW solutions. The SNO has also separated the energy spectrum in terms of day and night to determine if there is a solar neutrino flux difference during the day and night. To accomplish this it is necessary to determine if there are any day/night dependent systematics. For this reason, calibration sources were deployed during the night, and the rate of known sources of background were compared during the night and day. The day/night asymmetry is expressed as:

$$\mathcal{A} = 2 \frac{\Phi_N - \Phi_D}{\Phi_N + \Phi_D} \quad (3.10)$$

The asymmetry associated with each neutrino reaction is shown in Table 3.2.

SNO's day and night energy spectra have also been used to produce an MSW exclusion plot similar to Figure 2.13 under the assumption of two neutrino flavor oscillations. Various MSW solutions were assumed (i.e. a particular value of δm^2 , MSW mixing angle and total

Asymmetry	Value
$\mathcal{A}_{CC}$	$+14.0 \pm 6.3^{+1.5}_{-1.4}$
$\mathcal{A}_{ES}$	$-17.4 \pm 19.5^{+2.4}_{-2.2}$
$\mathcal{A}_{NC}$	$-20.4 \pm 16.9^{+2.4}_{-2.5}$

Table 3.2 : *The day/night asymmetries for the 3 neutrino reactions [38].*

^8B flux) and convolved with the SNO detector response to produce a prediction of the CC, ES and NC neutrino fluxes during the night and the day. A χ^2 fit is then performed of the sum of the expected fluxes to the neutrino energy spectrum for the night and day. The SNO-only iso-signal contour plot for various MSW solutions is shown in Figure 3.16(top). If the analysis is extended to include the fluxes measured by the Homestake (Cl), Gallex+GNO (Ga), experiments and the 1248 day day/night energy spectra from Super-Kamiokande, the MSW plot excludes the small mixing angle (SMA) and vacuum oscillations solution (VAC) to the SNP. This is shown in Figure 3.16(bottom). The strongly favoured MSW solution is the large mixing angle (LMA) oscillation scenario. However, the LOW solution is still allowed.

In June 2001 the SNO collaboration entered the next phase of the experiment, the addition of NaCl to enhance its ability to detect the neutral current. As of the completion of this thesis, SNO has not completed this analysis. It is important to emphasize once more the importance of the LEB in extracting the solar neutrino reaction fluxes. In the analysis of the salt data the isotropy differs from the case of pure D_2O fill. Therefore, the *In Situ* is modified to allow determination of the background. Furthermore, in this next stage of the analysis, the SNO detector is treated as an entirely new detector, thus, careful analysis of the LEB is necessary. In the next chapter the various LEB are surveyed and the motivations for a new LEB calibration source are presented.

Figure 3.16 : *MSW exclusion plot for [TOP] SNO only day/night spectral data and [BOTTOM] including the Cl, Ga, fluxes and the Super-Kamiokande day/night spectral information [38].*

Chapter 4

The Low Energy Backgrounds and the PCS

4.1 Introduction

To make an accurate measurement of the CC/NC ratio, the background, defined as any process giving Čerenkov light that is detected, but is not due to the particular ν interaction of interest, must be very low. Since we expect about 10 counts/day from each of the ν detection reactions, this requires the background to be comparable to this rate. The background comes from two main sources. First, there is the background due to the interaction of cosmic rays with the detector and the rock surrounding it. Second, there is the background due to the decay of naturally occurring isotopes in the detector components. The cosmic ray background is not a problem because the SNO detector is built 2.1 km below ground providing adequate shielding against cosmic ray muons, so that only about 70 muons/day will pass through the active volume of SNO. A more troublesome form of the background particularly at low energies is the inevitable thorium (Th) and uranium (U) that are present in the detector components themselves. The main contamination comes from beta particles and gamma-rays produced in the

^{232}Th and ^{238}U chains (see Figure 4.1 and Figure 4.2) and mimic the signal produced by a neutrino interaction. Indeed, the main challenge to the SNO Collaboration has been to construct the detector out of materials whose activity is low enough to make the signal to background ratio acceptable and to invoke protocols to maintain it that way ¹.

The low energy background coming from the Th and U chain manifests itself as a background in the D_2O fiducial volume in two ways. First, the low energy backgrounds produce $\beta - \gamma$'s which:

- Deposit electromagnetic energy inside the D_2O exceeding the trigger threshold.
- Misconstruct inside the D_2O fiducial volume.
- Exceed the trigger threshold due to the finite energy resolution of the detector.

The effect of this activity on the detector response is that the background increases exponentially toward lower energies and higher radii (known as the “Čerenkov tail” or “background wall”). This ultimately fixes the energy threshold for the detector and limits the fiducial volume of the detector.

The second consequence of backgrounds in SNO is that any γ -ray that has an energy greater than 2.223 MeV may photo-disintegrate the deuteron and then will appear as a NC signal. As mentioned before, this is a background that is a ‘perfect disguise’ to the neutral current, because there is no way to distinguish a free neutron from the NC from a free neutron produced from natural radioactivity coming from detector components ². This has the important consequence that the shape of the energy spectrum of the NC background and the NC signal are the same which means that we can not use data cuts to reject this background. For this reason, the only way we can account for this background is by quantifying what fraction of the NC background

¹My personal bias is that many cleaners, technicians and operators underground deserve a lot of recognition since they have helped ensure and maintain a low concentration of mine dust.

²In the past it was hoped that these backgrounds could be rejected based on the fact that the neutron would be preceded by a beta producing Čerenkov light in SNO (‘lookback technique’ [68]). However, at this time it appears that this is not a viable technique.

Figure 4.1 : The ^{232}Th decay chain and a simplified decay scheme for the troublesome ^{208}Tl beta decay

Figure 4.2 : The ^{238}U decay chain. Also showing the simplified decay scheme for the ^{238}U beta decay

is present in the neutrino data set (see Section 3.4).

The primary isotope producing this background is ^{208}Tl in the bottom of the ^{232}Th chain, which undergoes beta decay leading to a 2.615 MeV gamma. This branch occurs 36% of the time a ^{212}Bi decay occurs. In the ^{238}U chain, ^{214}Bi produces a number of γ -rays exceeding 2.2 MeV. However, this is not expected to be as serious a background as that due to ^{208}Tl decay because this reaction only occurs 2% of the time a ^{214}Bi decay occurs. See Figure 4.1 and Figure 4.2 for the details of the decay schemes for these isotopes. The events due to the presence of Th and U in the various materials out of which the detector is constructed, is displayed in figure 4.3 for 240 days of operation. The remainder of this focuses on the backgrounds of individual detector components, ways of assaying the amount of background present and motivations for constructing the Proportional Counter Source.

4.2 Overview of the Backgrounds by Detector Components

To understand the backgrounds present in SNO, it is necessary to look at the β 's and γ 's due to the Th/U in each component out of which the detector is composed. The background in each component has its characteristic shape in the response of the detector. Therefore, many of the backgrounds present in the data may be reduced by employing various cuts (fiducial and otherwise) in the analysis. The detector response due to the ^{208}Tl and ^{214}Bi present in the detector components is shown in Figure 4.3.

4.2.1 Cavity and Rock Surrounding the Detector

One of the principal reasons for choosing the particular site for the SNO detector was the low activity of the Norite rock (3.3 ppm Th, 1.2 ppm U) surrounding the cavity. Since the amount of Norite can not be changed, only by shielding the detector from the rock by light water have

Figure 4.3 : The estimated ^{232}Th and ^{238}U background level (width of the line corresponds to the uncertainty in the analysis) compared to 240 days of D₂O neutrino data (sum of NC, ES, CC, and NC background). Taken from [69]

the backgrounds been controlled. The rock is so far from the active volume of the detector that the β 's and low energy γ 's are all absorbed and do not make it to the D₂O. However, a fraction of the high energy γ 's ($E > 5 \text{ MeV}$) created by $(\alpha, p\gamma)$ and by (n, γ) on light elements in the rock may make it past the PSUP, and reconstruct inside the active volume of SNO. Simulations were done to track these γ 's [70] to the PSUP and study where these reconstruct. It was found that in general only the γ 's that cross the PSUP sphere pointing radially inward make it to the D₂O. In this study, it was also found that 90% of the γ 's produced in the rock that make it to

the D₂O come from the waist region (defined as the region 4.5 m above and below the equator). This is where the rock is closest to the D₂O and thus, where there is the least amount of light water shielding.

4.2.2 Backgrounds from H₂O, D₂O and AV

The main sources of these backgrounds are the Th and U that are present in the H₂O, AV and D₂O. These backgrounds are unique in the sense that most of these components are in the field of view of the PMTs and thus not only γ 's but also β 's are observed. This constrains the amount of Th, U and ⁴⁰K³ The concentrations tolerated by the SNO Collaboration are shown in Table 4.1 for the H₂O, AV and D₂O and are known as 'target levels' for these components.

Component	Mass(10 ³ kg)	Th(g/g)	U(g/g)
D ₂ O	1000	3.7e-15	4.5e-14
H ₂ O	1667.7	3.7e-14	4.5e-13
Acrylic	30.0	1.9e-12	3.6e-12

Table 4.1 : *Masses and concentration of ²³²Th, ²³⁸U in internal detector components*

Assuming that the Th and U present are in secular equilibrium, the Monte Carlo calculated background from the ²⁰⁸Tl γ -ray is about 3 n/day. The corresponding background due to the ²¹⁴Bi 2.445 MeV γ -ray is much less of a problem at 1 neutron every 4 days. The events due to the background in the D₂O reconstruct uniformly throughout the D₂O active volume for NHIT>40 [70]. It is tolerated that the concentration of the H₂O may be considerably higher than D₂O, because only a small fraction of the γ -rays produced in the H₂O reconstruct within the D₂O active volume. Monte Carlo simulations have demonstrated that about 1 neutron in 7 days are expected due to the backgrounds in the H₂O. By far the highest internal background comes from the AV, about 6.5 n/day. Radial distributions of reconstructed events show that if

³⁴⁰K may be present in materials and can be a problem for SNO in the sense that it produces many low energy γ -rays which can interfere with various analysis techniques

higher NHIT thresholds are imposed, the background in the acrylic region dominates.

4.2.3 PSUP and the PMTs

The PMTs are supported on the PSUP stainless steel (~ 10 ppb Th/U) geodesic structure. Early simulations have shown [71] that about 14 γ -rays/day with $E > 5$ MeV are released into 4π . A more pervasive background is the Omega reflector and the PMT base itself. The Omega reflector produces an order of magnitude higher background than any other PMT component. Later simulations suggest that in total about 117 γ -rays/day [70] that have an energy above 5 MeV are released isotropically. Recent analysis of Th calibration sources deployed at radii close to the PSUP shows that just as backgrounds coming from the rock, the γ -rays from the PSUP and PMTs appear to be pointing inward. This is shown in Figure 4.4 where the cosine of the angle between the fitted direction ($\vec{U}$) and the vector from the center of the AV to the reconstructed event ($\vec{R}$) are plotted for encapsulated acrylic Th sources deployed at $R=840$ cm and $R=600$ cm. It is seen that for the Th source deployed near the PSUP most of the events reconstruct with a direction inward ($\vec{U} \cdot \vec{R} < 0$), whereas for the Th source deployed near the AV the same fraction of events reconstruct inward as outward. The radial distributions of the PMT and PSUP γ 's are shown in Figure 4.5. In the figure it is seen that a small fraction of events due to Th/U resident on the PSUP reconstruct within the AV.

In Figure 4.5 it is clear that at increasing radii (corresponding to larger volume shells), the number of events reconstructed actually decreases. This is because the reflectors that support the PMTs shield the γ 's from other adjacent PMTs. It has been shown [73] that based on simple arguments, only one γ -ray in 10^6 simulated actually reaches the D_2O . However, the problem is that many PMT γ 's reconstruct inside the D_2O , as a consequence of an artifact of the event fitter used. This so called 'fitter pull' [74] has been decreased in new types of fitters.

Figure 4.4 : *The figure shows the cosine of the angle between the fitted direction ($\vec{U}$) and the vector from the center of the AV to the reconstructed event ($\vec{R}$) for encapsulated acrylic thorium sources deployed at $R=840$ cm and $R=600$ cm [72]*

4.2.4 Other Transient Sources of Activity

There are other sources of activity which are not necessarily supported as the above sources but appear as transient backgrounds and therefore necessitate a scheduled assay of the background levels. An example of such backgrounds is when there is a sudden pressure change in the laboratory air causing mine air ⁴ to mix with any water that is exposed. SNO has a nitrogen cover gas to act as a barrier against this although these pressure swings are still a concern. A second transient background occurred when a vacuum pump on the H₂O process degasser seizes and a gate valve failed to close, which actually occurred in SNO in November 2000. This caused mine air to come into direct contact with the H₂O for several days. A third source of background [72] occurs from water that is not properly mixed due to stagnant water at the top of the vessel and improper recirculation in various areas. At the moment the circulation patterns are not well known in the D₂O and studies are underway to investigate these. Other sources of

⁴Mine air is the enemy. Mine air contains $\sim 100\text{-}300$ Bq/m³ Rn-222 [75]

Figure 4.5 : *The SNO detector response due to Th/U activity on the PSUP showing the decrease of γ 's reconstructed with a radius less than the radius of the AV. Adapted from [69]*

potential activity are the calibration sources that carry surface activity into the waters.

4.3 Activity Assay techniques

From the preceding discussion it is clear that to do an accurate measurement of the CC, ES and NC, it is imperative that the contribution of the low energy background to the neutrino signal must be known. SNO has developed many different techniques to assay this contribution and determine whether the the SNO waters (heavy and light) are below or above the target levels (see Table 4.1). In addition, the concentration of Th and U in these waters must be seen as a dynamic quantity and assayed very often to determine whether there has been contamination

from changes in conditions occurring in the waters.

The various assay techniques can be divided into two groups: the *Ex-Situ* techniques which directly assay the waters off-line and the *In-Situ* technique which uses the differences in detector response to various backgrounds to quantify the amount of Th/U present in the D₂O and H₂O.

4.3.1 Ex-Situ Assay Techniques

There are several *Ex-Situ* techniques SNO uses to quantify the background due to the Th and U chains. Each analysis technique is described briefly below.

Seeded Ultra-Filtration Technique

This technique relies on passing a large volume of water onto HTiO coated ultra-filtration fibres. The HTiO acts as an inorganic ion-exchanger and extracts the Radium, thorium and Lead from the water. The technique relies on five steps: deposition, extraction, elution, secondary concentration and the counting of the sample. The deposition consists of depositing the HTiO onto the ultra-filtration membranes and placing the filters into the columns. The columns are then taken underground, and the water to be assayed is passed over them. The columns are sealed and brought back to surface. The column is eluted with 15 ml nitric acid and further concentrated to ~10 mL. Then, the 10 ml of concentrate is added to 40 g of Optiphase Hi-Safe 3 liquid scintillator and placed in a plastic jar. The jar is optically coupled to a PMT for counting⁵. The electronic logic and analysis of the PMT is optimized to tag the two $\beta - \alpha$ delayed coincidences in the Th (300 ns for ²¹²Po) and U (164 ms for ²¹⁴Po) chains. All $\beta - \alpha$ events with a coincidence time window of <700 ms have their amplitudes recorded for off-line analysis. The amplitude data is used for background rejection due to chance coincidences. These

⁵While at Carleton I was involved with the testing and development of a prototype liquid scintillation counter.

counters have been found to be sensitive to ~ 1 count per day for the Th chain and a few counts per day for the U chain. The assays are usually conducted every 1.5 months and consists of approximately 200 tons of D_2O and 30 tons of H_2O being assayed. For the D_2O the HTiO-SUF system currently has a sensitivity of $\sim 1.2 \times 10^{-15}$ $^{232}Th/gD_2O$ and $\sim 7 \times 10^{-16}$ g U/gD_2O for 200l of D_2O [76].

MnO_x Bead Technique

This technique consists of passing large amount of water over columns loaded with MnO_x beads. The beads extract the Ra and to a lesser extent other elements, such as Th and Pb, from the flowing water onto the beads. However, there is a possibility that minute particles of MnO_x loaded with radioactive contaminants extracted on the beads (called fines) may flow back into the water. The probability of MnO_x fines entering the AV is reduced by doing a subsequent rinse with H_2O ⁶. Fines flowing back into the water could cause the radioactivity measured to be underestimated and increase the radioactive contamination of the water.

The columns are then sent to surface and dried. The dried columns are then attached to a rig (see Figure 4.6) with an electrostatic counter attached (ESC). The Rn produced as the Ra decays in the column is swept into the active volume of the ESC using a N_2 carrier gas. The ESC's consist of two sides of a concave Aluminum surface with a silicon photodiode as an α -particle detector. Once the Rn decays to Po, the Po isotopes (75% are ionized [47]) are carried under the influence of an electric field to the silicon photodiode. The Po atoms then decay by emitting an α -particle and are detected.

A typical spectrum has peaks from the alpha decay of ^{216}Po and several other peaks from the decay of ^{212}Pb if the sample is Th chain dominated and peaks corresponding to ^{214}Po and ^{218}Po if the spectrum is U chain dominated. A typical counting period consists of 10 days to

⁶While at Carleton University I was involved in a study of the effect of these fines and how to reduce them [48], [49], [77].

Figure 4.6 : Schematic diagram of gas flow through MnO_x column and ESC [77]

ensure that if the spectrum is U chain dominated, the various Po isotopes driven by the 3.8 day ^{222}Rn will decay. The spectrum is then compared to the background spectrum obtained with the same column before the column is used in the water assay.

The data analysis consists of first fitting each of the Po peaks to determine the number of counts in each peak. The next step is to determine the concentration of Ra that produces the observed distribution of counts in each peak. This is described in detail in [77].

Monitor Degasser (MDG) Technique

The problem with the previous two techniques is that measuring the ^{226}Ra concentration in the water does not completely determine the true background due to the U chain. This is because a small contribution of ^{222}Rn from laboratory air can lead to substantial disequilibrium between ^{226}Ra and ^{214}Bi . Therefore, depending on the Ra measurements for determining the background due to the U chain might substantially underestimate the ^{214}Bi photo-disintegration background. The MDG assay technique is developed to tackle this problem ⁷. In this technique several tons of water are passed through a degasser which allows the dissolved gasses to be separated from the liquid phase. The gasses on the outlet of the degasser are pumped out with a vacuum pump using the water vapour as a carrier. The vapour is then passed through a first cryogenic trap which traps the water vapour and passes the dissolved gasses (Rn , O_2 , N_2 , CO_2) into other cryogenic traps at -192°C . The trap is then heated and the gasses are thermally transferred into a Lucas Cell used as a Rn counter. The Lucas Cell is constructed out of acrylic and consists of a hemispherical surface covered with a ZnS scintillator. The scintillator emits light when an α -particle from ^{222}Rn decay strikes it. The light from the α -particle is detected using a PMT which views the Lucas Cell through a clear window. The count rate as a function

⁷While in Sudbury I have spent a large amount of time working on the MDG technique, understanding the background contribution of various components of the monitor degasser and recirculation loop and assessing the variation of the background in the Lucas Cells over time [78], [79].

Figure 4.7 : *Schematic of radon collection and concentration apparatus. Parts are not drawn to scale. V shows a valve and QC labels the quick-connector on the Lucas cell. The valves are drawn in the position for extraction from the degasser, during which time the primary radon trap is immersed in liquid N_2 [80].*

of time is measured and the concentration of the initial Rn in the water is determined. The set-up is shown in Figure 4.7.

4.3.2 In-Situ Assay Techniques

This assay technique uses the specific differences in the PMT distributions between ^{208}Tl (Th chain) and ^{214}Bi (U chain) to statistically distinguish the two isotopes and determine their concentrations in water. The technique uses the following facts:

- The Q value of ^{214}Bi is 3.27 MeV whereas that for ^{208}Tl is 5 MeV
- Every decay of ^{208}Tl produces a 2.614 MeV gamma and some additional low energy γ -rays whereas with ^{214}Bi this does not necessarily occur. This is shown in Figure 4.8 where the γ -ray multiplicity is plotted for both decays as a function of NHIT.

This difference implies that the ^{208}Tl always produces more than one γ -ray (see Figure 4.8) and therefore, its PMT distributions look more isotropic than that from the decay of ^{214}Bi . In

Figure 4.8 : Comparison of the multiplicity of γ -rays for ^{208}Tl (solid) and ^{214}Bi (dashed) [81]

other words, it is possible to separate ^{208}Tl from ^{214}Bi statistically by looking at the isotropy of the event in a particular NHIT window. The isotropy parameter that has been adopted is known as θ_{ij} and is the average angle between all hit PMT pairs within the prompt light time window in an event. The differences between the two distributions is shown in Figure 4.9. This technique proceeds in several steps. First, standard data cleaning cuts are applied to reduce the instrumental backgrounds in each data set. Next, the data is selected in a particular NHIT window, and a maximum likelihood fit is done of the observed θ_{ij} distributions to a linear combination of PDF's for the Monte Carlo simulated θ_{ij} distributions for both ^{208}Tl and ^{214}Bi distributions. The fitted amplitudes are then converted to a concentration for the ^{232}Th and ^{238}U in the water. As the fit is done to Monte Carlo θ_{ij} distributions, we need to be certain that the Monte Carlo distributions correctly simulate the θ_{ij} distributions of a point source of ^{208}Tl and ^{214}Bi .

Figure 4.9 : The θ_{ij} distributions for both ^{208}Tl and ^{214}Bi (shaded) for a point source at the center of the SNO active volume. Also shown is the absolute value of the difference of the two distributions. This is discussed further in Chapter 6

Unfortunately, determining the concentration of the various isotopes from the number of events that pass the θ_{ij} cuts in a particular NHIT window suffers from systematics. The NHIT region where the *in-situ* technique is applied is approximately NHIT 25-35 and at this high NHIT, narrow window, a very small fraction of actual ^{208}Tl or ^{214}Bi decays pass all the cuts. Therefore, it is difficult to prove that the Monte Carlo is correct at this level.

Problems with Acrylic Sources: *In-Situ* SNO has developed several low energy background calibration sources (described in previous chapter) known as ‘encapsulated acrylic’ sources which have been used to predict the ratio of events in a NHIT window compared to the actual number of decays. However, as was described in the previous chapter, these sources suffer from uncertainty in simulating the optics of the acrylic in which the background sources are encapsulated adding uncertainty in knowing this ratio to $\sim 40\%$. Recently, neutron activation on ^{23}Na has been used to compare the Monte Carlo θ_{ij} spectrum to data. These experiments greatly decrease the systematic uncertainty of knowing the ratio of events in a NHIT window

compared to the actual number of decays to $\sim 10\%$ [69]. However, the decay scheme of ^{24}Na is not identical to that of ^{208}Tl , so there is still some question about the ability of the Monte Carlo to calculate the ratio of events that pass the cuts to the number of ^{208}Tl decays. Furthermore, the activation of ^{23}Na can only be done in the D_2O since only there NaCl is present. The optics in the H_2O is different from the D_2O , so we should not expect that the Monte Carlo will be able to predict this ratio as well in the H_2O as in the D_2O . To summarize we do not have a *Na-like* calibration source that we can deploy in the H_2O .

The next problem with acrylic encapsulated sources is that they are not tagged or triggered, allowing other backgrounds that occur during the run to be included in the data as well as the neutrons resulting from γ -ray photodisintegration of the deuteron. For these reasons the Proportional Counter Source has been developed that aims to overcome these difficulties.

4.4 Determining the Number of Events due to the Čerenkov Wall

4.4.1 Tail-to-Neutron Ratio to Determine the Internal Čerenkov Background

This technique consists of using Monte Carlo studies of background sources to determine the ratio of photo-disintegration neutrons to the number of events which are composed of the Čerenkov tail. The Čerenkov tail is defined as the events in the high energy tail of the low energy background wall (see Figure 4.3). These events may exceed the energy analysis threshold and contaminate the neutrino data set. To use the Monte Carlo is justified because the D_2O optics are well understood and encapsulated acrylic sources show that the Čerenkov tail from the background wall is not large. The same cuts were applied to the photo-disintegration

neutrons as were done to the Čerenkov tail to extract the tail-to-neutron ratio. The systematic uncertainty is calculated by smearing various parameters, such as the energy scale, θ_{ij} value and energy resolution. The number of detected photo-disintegration neutrons allows us to determine the number of Čerenkov tail events [69].

4.4.2 High Radon Spike to Determine External Čerenkov Background

In November 1999 there was an anomalously high amount of radon dissolved in the water. This occurred because a gate valve failed to close when the light water process degasser failed and brought the water in contact with laboratory air. A similar event occurred in November 2000. The water was assayed at this time using the *ex-situ* techniques and it was found to contain 50 times more radon than usual. This allows an opportunity to calibrate the background wall to the U chain and to ascertain the leakage of the events into the neutrino data set. The shape of the Čerenkov background observed is fit to the Monte Carlo ^{214}Bi shape. The amplitude parameter extracted is assumed to correspond to the value of the U chain concentration in the light water obtained using the *ex-situ* assay performed during the same period. The shape of the U chain Čerenkov tail can then be calculated for the concentration of radon normally dissolved in the H_2O [82].

4.4.3 Radial Distribution Fit to Determine External Čerenkov Background

This technique uses U and Th encapsulated sources deployed at various positions throughout the D_2O to determine PDF's in R^3 for background in the D_2O , H_2O , AV and near the PSUP. The technique aims to overcome the fact that the Čerenkov light output from the acrylic sources does not match well the prediction made by SNOMAN. Since the reconstructed radial distributions match the Monte Carlo well, they are used as a parameter to fit the observed neutrino data. The R^3 PDF's are constructed by volume-weighting the R^3 distributions for many U and

Th encapsulated acrylic sources throughout the detector active volume. An extended maximum likelihood fit is then performed of a linear combination of the R^3 PDF's to the observed neutrino data set. One of the significant problems with this technique is the fact that there are insufficient statistics at the analysis threshold used by SNO (5.5 MeV), so the fit is performed at a lower energy where the data set is not statistics-limited and extrapolated to 5.5 MeV [83].

4.5 Problems with Determining the Low Energy Background

Many studies that have been performed to determine the low energy background have used the encapsulated Th and U sources. However, as has been emphasized earlier, the acrylic sources have optical effects which make the sources difficult to use for comparing with Monte Carlo. These problems are summarized below [84], [81]:

- Discrepancies were observed in the positional and radial reconstruction as compared to Monte Carlo.
- The amount of light output from the acrylic source is unknown and differs considerably from Monte Carlo.

For this reason the Th acrylic sources were shielded with a thin layer of Stainless Steel to stop the beta's Čerenkov production in the acrylic. This meant that the shielded Th source only simulates a ^{208}Tl 2.6 MeV γ -ray calibration source and does not deposit the full Q value of energy in the water as the isotope present in the water would. However, despite these problems, the shielded acrylic source was used to estimate the absolute energy scale uncertainty for the *in-situ* measure of the H₂O radioactivity. The uncertainty in knowing the absolute energy scale due to source optics was found to be 42%. This is because the Monte Carlo underestimates the prediction for the background wall for the shielded source [85]. For these reasons it is important to deploy a new generation calibration source with source optics that match better what is expected of a point source in the water.

Furthermore, studies done with the ^{16}N source suggest an offset in the θ_{ij} distribution between Monte Carlo and data. This offset is significant and corresponds to a 18% systematic uncertainty of extracting the concentration of Th in the H_2O . If this discrepancy between Monte Carlo and data is not solved, this could become an important systematic in extracting the neutrino signals.

4.6 Proportional Counter Source (PCS)

The problems in using the acrylic encapsulated sources and in the analyses described in the previous sections have led to the development of a new calibration source. This source aims to add little distortion to the Čerenkov spectrum, high rate and intends to be tagged/triggered so that backgrounds due to chance coincidences during a run will not contaminate the signals. This has been accomplished for the isotope ^{228}Th by electroplating ^{228}Th directly on the anode of a proportional counter. The proportional counter is in the form of a cartridge which fits into a thin-walled protective polycarbonate cylinder. When the ^{228}Th decays betas and gammas are emitted just as is the case when a point source of ^{228}Th is placed in the SNO active volume. The wall of the polycarbonate is very thin, such that the beta adds little Čerenkov light ⁸ to the point source Čerenkov spectrum (see discussion in Chapter 3.1.2). Furthermore, the PCS will be tagged/triggered by using the signal from the proportional counter. The source has also been designed to have a large event solid angle, so that only 4% of straight line paths away from the source intersect with the end caps of the source geometry. The PCS has been designed applying the following criteria:

⁸For a beta particle with relativistic $\beta \sim 1$ travelling normal through the polycarbonate only 15 extra Čerenkov photons are produced as compared to water.

[1] PCS must closely approximate a ^{228}Th point source

Thorium is present throughout the active volume of SNO and one can conceptualize this as a collection of point sources throughout the active volume. It is the purpose of the PCS to determine the responses of the SNO detector to thorium at every point in the active volume. Once these are known, PDFs describing the shape at each point are weighted according to the actual activity at each point in SNO. In this way, a PDF can be built up describing the response to all the activity in SNO. For this reason, it is imperative that the PCS produces minimal distortion to the Čerenkov spectrum such that the SNO detector response due to the PCS is similar to that of a ^{228}Th point source. This has been achieved by housing the ^{228}Th source in a cylinder with a 0.7 ± 0.1 mm polycarbonate wall. Details on the design are described in the next chapter.

[2] PCS can be triggered or tagged so that its contribution can be identified with respect to the rest of the triggers.

The PCS can be run in a tagged mode. Therefore, when a beta or α -particle exceeds the discriminator threshold of the PCS, a logic pulse is sent to one of the inputs of a FEC. If the decay observed in the PCS is due to a ^{212}Bi or ^{208}Tl beta, the Čerenkov radiation may trigger the SNO NHIT100 trigger and the event is written out. This allows the NHIT spectrum to be determined from the trigger threshold to high NHIT. The PCS can also be run in a mode where SNO is triggered whenever a pulse is seen in the proportional counter. This allows the full NHIT spectrum to be determined. In both modes we determine the NHIT spectrum **independent of the photo-disintegration neutron that may follow the initial $\beta - \gamma$ cascade.**

[3] PCS ^{228}Th source activity must be known with high precision

The PCS sources are essentially self-calibrating. This is due to the self-consistency of many of the rate equations describing various event classifications. This is described in detail in Chapter 6.

[4] PCS position must be well determined in SNO

The PCS sources can be deployed throughout the D_2O and H_2O and (since the source geometry is well known) the position is assumed to be the position reported by the manipulator computer. This is in contrast to other ‘container-less sources’ such as the proposed radon spike and the ^{24}Na source whose geometry is not well defined.

[5] PCS cannot pose a risk to SNO

Unfortunately, since the ^{228}Th cartridge is surrounded by a thin 0.7 ± 0.1 mm polycarbonate wall, it is very important to ensure that the PCS will not fail. Furthermore, various fail-safe mechanisms must be in place to prevent contamination of the SNO active volume if a breach of the water seal occurs. This, in addition to the advantages above, has been one of the primary design criteria for the development of the source, which is described in detail in the next chapter. If a failure occurs where the ^{228}Th contaminates the SNO active volume, the background due to ^{228}Th would increase by *5 orders of magnitude* compromising the SNO experiment.

Satisfying the above 5 criteria constitutes the success of the design.

4.7 PCS Physics Motivations

4.7.1 Deploying the PCS in D₂O in tagged mode

By running the PCS in tagged mode in the D₂O, the ²⁰⁸Tl NHIT spectrum can be measured with high precision from the NHIT trigger threshold to high NHIT independent of the photo-disintegration neutron and other backgrounds. Some important motivations for running in this mode are:

(1) Calibrate the ²⁰⁸Tl $\beta - \gamma$ events in the Čerenkov tail

This will allow us to measure the number of $\beta - \gamma$ events in Čerenkov tails to quantify how many events due to thorium populate the neutrino data set. The advantage of using the PCS is that it is not necessary to depend on fitting the events to know which events are due to ²²⁸Th decay, since we will be able to associate each individual event seen in the PCS with a response in SNO. The fact that the events need not be fit not only increases the efficiency of seeing the events in the tails of the NHIT distribution, but also allows us to determine the number of events under the neutron peak independent of other backgrounds, or systematics in the fitters. In this way the systematic uncertainty in the calculation of the number of events under the neutron peak will to be due to the uncertainty in knowing the activity of the PCS ²²⁸Th sources rather than the uncertainty in modelling the sources.

From Monte Carlo calculations 1.3% of ²⁰⁸Tl point source events deployed at the center of the D₂O exceed NHIT=30. The PCS distorts ⁹ the spectrum and produces 23% less events with NHIT>30. Thus, we can fit a particular NHIT window of the measured low energy background wall with the spectrum observed from the PCS in the same NHIT window and calculate what activity the wall corresponds to if it were all due to contamination from thorium. We can

⁹The implementation of the PCS geometry into the SNOMAN Monte Carlo is described in full in Chapter 6.

then calculate the number of tail events which we expect will have high enough energy to be under the neutron peak. For 3/4 hours running with a 1kBq ^{228}Th source, we have $>10^4$ events exceeding $\text{NHIT}=30$. This is shown in Figure 6.18 (Figure discussed in chapter 6) for a ^{208}Tl point source, and the PCS full geometry to be described in Chapter 6.

(2) Determination of shape of ^{208}Tl θ_{ij} distribution

Based on Monte Carlo, it is expected that there is little distortion to the PCS ^{208}Tl θ_{ij} distribution as compared to the ^{208}Tl point source (see Figure 6.20 in Chapter 6). Quantitatively based on Monte Carlo the difference between the two θ_{ij} distributions when the peaks are fitted to a Gaussian is that the PCS θ_{ij} distributions has a shift of approximately 1% towards lower θ_{ij} as compared to the ^{208}Tl point source. Most of the error in the extraction of the thorium activity using the *In – Situ* technique comes from uncertainty in modelling the acrylic sources [81]. Furthermore, even when the ^{23}Na source is activated, it has been determined that the extracted Th level using the *in – situ* technique has a strong dependence on the difference between the data and Monte Carlo θ_{ij} distributions (Monte Carlo produces a θ_{ij} distribution with a mean that is 1% higher). Therefore, another motivation for deploying the PCS is to measure quantitatively the ^{208}Tl θ_{ij} distribution.

(3) Calibration of the number of events in a background monitoring window to number of ^{208}Tl decays

The background region for the θ_{ij} analysis is performed in a particular NHIT window, with particular cuts applied. Thus, it is necessary to be able to associate the number of events seen in the background window with the ^{228}Th activity. This is a major systematic of the ‘in-situ’ technique because encapsulated acrylic sources have significant distortion to the ^{208}Tl as compared to the free source in the θ_{ij} NHIT window.

(4) Determination of Cut Efficiency

The effect of the data cleaning on the neutrino data set using the standard suite of cuts needs to be determined. This analysis should be performed with tagged/triggered sources as was done in McCauley [66]. Doing this analysis with the PCS is an important compliment to our knowledge, particularly because the PCS is a low energy source.

(5) Determination of fitter Systematics

Since the PCS is a tagged/triggered source, we are able to associate every event seen in SNO with an event seen in the PCS. This allows us to determine the performance of the fitter in vertex reconstruction by determining the mean and width of the fitted vertex distribution.

4.7.2 Deploying the PCS in D₂O in triggered mode

By running the PCS in triggered mode in the D₂O, the entire ^{208}Tl NHIT spectrum can be measured independent of the photo-disintegration neutron and other backgrounds. Some important motivations for running in this mode are:

(6) Measurement of ^{208}Tl spectrum

As mentioned before, the PCS tagged or triggered allows us to measure the shape of the ^{208}Tl spectrum, independent of the photo-disintegration neutron that may follow. Measuring this shape will allow us to fit the background wall and extract the measured concentration [86]. It is suggested that if this shape of all the backgrounds ¹⁰ is known with high precision, we may be able to lower the analysis threshold to lower energies. In Figure 6.17 (see Chapter 6), the SNOMAN unfitted spectrum is shown for the PCS full geometry and a ^{208}Tl point source.

¹⁰An electroplated ^{226}Ra PCS source will be constructed shortly. This source will allow us to measure the SNO detector response from the ^{214}Bi $\beta - \gamma$ cascade of the ^{238}U chain.

(7) Variations in the ^{208}Tl peak position

In triggered mode the Monte Carlo predicts that the ^{208}Tl spectrum has a peak at $\text{NHIT} \sim 16$ and falls off with an exponential tail toward higher energies (see Figure 6.17 in Chapter 6). One can view the triggered PCS source as a single point low energy calibration source with a known shape, but unknown energy at the peak. This means that even if we do not know the precise energy of the peak, we will still be able to observe the variation in the mean and the exponential tail as the source is deployed throughout the D_2O . It is questionable whether we will actually be able to use the peak in the ^{208}Tl spectrum as a low energy calibration point, since the trigger efficiency shape is not well known. However, given that SNO currently does not have many low energy calibration sources the PCS may be useful in this regard, especially in the H_2O where we do not have a ^{24}Na source.

4.7.3 Deploying the PCS in H_2O in tagged mode

Since SNO does not have a ^{24}Na source in the H_2O , our knowledge of the detector response and cut efficiencies are not as well understood as it is in the D_2O . Some of the PCS physics motivations for deploying the PCS in H_2O are the following:

(8) Number of ^{208}Tl events reconstructing inside the D_2O

By running the PCS in tagged mode in the H_2O in various positions radially throughout the H_2O , the leakage of events reconstructing into the D_2O can be determined *independent of the photo-disintegration neutron* that follows. For example, for 200k PCS ^{208}Tl events (10 min running with PCS source ‘PCD’ shown in Table 5.1) with the PCS deployed at $R=653$ cm, we expect 200 events reconstructing inside the D_2O . Figure 6.25 (see Chapter 6) illustrates this for the PCS and ^{208}Tl point source Monte carlo.

(9) Efficiency of low θ_{ij} cut to discriminate against H_2O ^{208}Tl events in the D_2O

It has been observed that the θ_{ij} distributions of neutrino data have two peaks after low level cuts have been applied. It is believed that the low θ_{ij} peak is due to AV/ H_2O /PMT $\beta - \gamma$'s that contaminate the neutrino data set [81, 87]. Therefore a cut of $\theta_{ij} > 0.8$ (Note: G. McGregor employs a $\theta_{ij} > 1.0$ cut) has been applied to remove the external $\beta - \gamma$'s from the neutrino data set. If the PCS is deployed throughout the D_2O , AV and near the PSUP, the effect of this high level cut can be determined.

(10) Systematics in Vertex Reconstruction

There is a systematic shift in vertex reconstruction of the shielded encapsulated acrylic sources as we move closer to the PSUP (see [83], Figure 13). Figure 4.10 shows a distribution for R_{dev} (Distance between fitted vertex and known PCS position) for the PCS source deployed at $R=653$ cm where the ^{208}Tl point source is normalized to the PCS source. Since there is little difference between the shape of the R_{dev} distributions in Figure 4.10, deploying the PCS throughout the H_2O allows us to determine the systematics of fitter vertex reconstruction.

4.7.4 Deploying the PCS in H_2O in triggered mode

By running the PCS in triggered mode in the H_2O , the entire ^{208}Tl NHIT spectrum can be measured. Some important motivations for running in this mode are:

(11) Determination of energy scale throughout H_2O

V. Rusu recognized that the energy distributions of shielded encapsulated sources are not the same as neutrino data that reconstruct at the same radius as the source position in the H_2O . Consequently, V. Rusu [83] compensates for this effect by applying an energy shift to the neutrino data. In triggered mode we should be able to see the peak in the ^{208}Tl spectrum

Figure 4.10 : *The R_{dev} distribution for $NHIT > 25$ and $R_{dev} < 2m$ for the source at $R=653$ cm corresponding to ~ 10 minutes with a $1kBq$ ^{228}Th source*

and use this as a single point calibration to estimate variation in energy scale as the PCS is deployed at various radii. As mentioned before, the trigger efficiency may dominate the low energy SNO detector response so that we may not be able to use the peak as a single calibration point. However, in principle having this calibration point could be useful.

(12) Determination of AV PDF

The uncertainty due to AV $\beta - \gamma$'s is one of the largest uncertainty in V.Rusu's extended Maximum Likelihood R^3 analysis [88]. It will be useful to deploy PCS source 'PCD' near the AV both in the H_2O and in the D_2O to aid in determining the AV PDF.

This chapter presents some of the main backgrounds present in the SNO detector as well as some of the low energy background analyses that have been carried out. The main objective

of this chapter is to state some of the problems with the background analysis and discuss the physics motivations for the development of the Proportional Counter Source. The next chapter describes the design of the PCS and some of the problems and precautions with its deployment.

Chapter 5

PCS Design and Development

5.1 Introduction

In this chapter, a simple, accurate and direct calibration source is described for simulating the contributions to the background wall and the background neutrons in SNO. A proportional counter (PC) with one of the isotopes on the anode that are naturally present in SNO is used to tag the beta-decay with negligible effect on the beta's Cherenkov radiation, or the resulting gamma cascade. One can detect the subsequent Čerenkov light in SNO in coincidence with the PC signal with a resolving time of about 100 ns.

As described earlier, the PCS acts both as a proportional counter(PC) and as a source. The PC part of the PCS detects the betas and α -particles when a ^{228}Th decay occurs on the anode wire and then triggers or is tagged by the SNO electronics. Since the PC is an integral component of the PCS, the principle of operation of a proportional counter is described in the next section. In the following sections a component-by-component description of the design are presented. In the concluding sections the PCS testing, quality control and assurance are described. In the previous chapter the five main criteria of design are stated with the last element: *PCS can not pose a risk to SNO*. The main purpose of this chapter is to introduce

the reader to the PCS design and to convince the reader that the PCS will not compromise the physics of SNO.

5.2 Introduction to Proportional Counters

5.2.1 Principle of Operation

Gaseous detectors in their simplest form consist of a cathode (radius r_b) and a thin wire (radius r_a) as the electrode, with a voltage applied across the electrodes. In this geometry the electric field ($E(r)$) in terms of the electric potential ($\phi(r)$), radius (r) and applied voltage (V_0) is given as:

$$E(r) = \frac{-d\phi}{dr} = \frac{V_0}{r \ln(r_a/r_b)} \quad (5.1)$$

When a charged particle passes through matter, it ionizes the medium and leaves a trail of electron-ion pairs (primary ionization). The principle of operation of all of these detectors is the detection of charged particles by collecting the electron-ion pairs. Gaseous detectors can be operated in three different modes depending on the difference in the electric field across the electrodes. These are classified as ionization, proportional and Geiger-Mueller modes of operation. In the ionization region the number of ion-pairs collected is equivalent to the number of ion-pairs produced by the traversing charged particle. This means that this mode of detection is only used for charged particles that produce a large amount of specific ionization and seldom for low ionizing particles, such as beta's. However, in the proportional region of operating the detector the voltage difference (V_0) between the cathode and anode is high enough that the primary ionization electrons gain sufficient energy from the accelerating fields in the region close to the anode to further ionize gas molecules. The kinetic energy gained by a primary electron travelling between sequential collisions where $|r_1 - r_2|$ is the collision mean free

path (See Eqn 5.1) is given by:

$$\begin{aligned} K &= e \int_{r_1}^{r_2} E(r) dr \\ &= eV_0 \frac{\ln(r_2/r_1)}{\ln(r_a/r_b)} \end{aligned} \quad (5.2)$$

Consequently, if the average energy gained K between two sequential collisions is greater than the ionization potential of the gas, the primary electron will produce more ion-pairs and result in a "Townsend Avalanche" [46]. Therefore, the amount of charge released will be proportional to the charge due to the primary electron-ion pairs (Ne) by a factor M , known as the gas amplification factor. Therefore, the amplitude of the signal induced on the anode V will be proportionally increased by a factor M to the number of primary ion-pairs created in the avalanche.

$$V = -M \frac{Ne}{C} \quad (5.3)$$

In addition, since the electric field (see equation 5.1) increases as $1/r$, the voltage can be tuned so that the amplification occurs over a few wire diameters from the anode wire. In this way the amplification factor M will be insensitive to where the charged particle track has occurred in the counter.

5.2.2 Selection of Fill Gas

The selection of the counting gas used in a proportional counter is based on several factors, low working voltage, high gain, good proportionality and high rate capability. To operate at low voltages ($\sim 2-3$ kV), noble gases such as argon are preferred since they require low electric field intensities for avalanche formation. Argon is the most common gas used for this purpose because of its higher ionization and low cost. The disadvantage of using argon gas is the fact that it results in breakdown at about 10^3-10^4 gain. The reason for this is that during the avalanche

process excited atoms are formed which only de-excite radiatively. These photons can produce photoelectrons at the cathode via the photoelectric effect which trigger new avalanches leading to breakdown. This problem can be removed by adding a polyatomic molecule, such as CH_4 . These polyatomic molecules act as quenchers by absorbing the radiated photons that cause the secondary avalanches. P10 (90% argon, 10% methane) mixture is commonly used in proportional counters and in the PCS. P10 has a long operating plateau which allows one to go to higher voltage and thus higher gains before the onset of breakdown. The number of ion pairs produced in the PCS is approximately 98 ion pairs/cm of beta track length.

5.2.3 Energy Loss of Beta's and Alpha Particles in the PCS

The energy loss of charged particles ¹ through a gas is described by the Bethe-Bloch formula [46]:

$$\frac{dE}{dx} = D\rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e \gamma^2 \beta^2 c^2 W_{max}}{I^2} \right) - 2\beta^2 \right] \quad (5.4)$$

where, $D = 0.1535 \text{ MeV cm}^2/\text{g}$

m_e = electron mass

Z = Atomic number of absorbing medium

A = Atomic weight of absorbing medium

ρ = Density of absorbing medium

I = mean excitation potential

z = charge of incident electron in e

W_{max} = maximum energy transfer in a single collision

From the formula it is noted that mass of the charged particle does not appear. Rather the in-

¹Note that the Bethe-Bloch formula for an electron differs slightly in the term multiplied by the leading term. This is because the calculation must take into account the fact that the incident and target electron are indistinguishable and that the mass is so small that the assumption that the incident particles are undeflected during the collision is invalid. This is a small correction and is ignored in the following discussion.

fluence of the mass of the incident particle has been absorbed into the relativistic beta factor. The energy loss is inversely proportional to the square of the relativistic β factor. This means that particles with high β will lose less energy than particles with low β , as can be intuitively understood by noting that a charged particle that is travelling slower has more time to transfer its energy to the medium than a particle that is travelling faster. Considering the fact that α -particles at nuclear decay energies are essentially non-relativistic and that α -particles have higher charge than betas, α -particles will deposit much more energy in the gas than beta particles. For example, in the ^{228}Th chain α -particles have a maximum kinetic energy of 9 MeV compared to a mass of ~ 4000 MeV so that their relativistic $\beta < 0.07$. However, for a typical beta of 1 MeV the relativistic beta factor is ~ 1 . Consequently the typical energy loss of an α -particle in the gas is 800 times higher than a beta in the ^{228}Th chain. Since the number of ion-pairs produced in the gas is approximately proportional to the energy deposited in the gas, the number of ion pairs produced by an alpha track in the PCS is 3 orders of magnitude higher than that of a beta. This fact is used in the classification of events observed in the PCS and is described in more detail in Chapter 6.

5.2.4 Pulse Shape

Derivation of the pulse shape for point ionization

The pulse shape of a proportional counter for a point ionization event was first described from empirical results by Ramsey [89] in 1940. However, it can also be derived based on the conservation of charge and energy. Suppose a localized point charge Q in a proportional counter, drifts under the influence of an electric field toward the anode. Then the potential energy ab-

sorbed (dW) by the particle moving through a difference in electric potential $d\phi$ is: ²

$$dW = -Qd\phi(r) = -Q \frac{d\phi(r)}{dr} dr \quad (5.5)$$

If we further assume that the power supply reacts slowly with respect to the drifting charges, the energy in the system is conserved. In a cylindrical capacitor the electrostatic energy contained in the applied electric field is written as:

$$dW = CV_0 L dV \quad (5.6)$$

where C is the capacitance of a proportional counter of length L . The last two equations allow us to solve for the infinitesimal change in the voltage dV induced across the electrodes:

$$\begin{aligned} dV &= \frac{dW}{CV_0 L} \\ &= \frac{-Q}{CV_0 L} \left(\frac{d\phi(r)}{dr} \right) dr \end{aligned} \quad (5.7)$$

Now when a positive voltage is applied to the anode and the cathode is grounded, the much faster moving electrons will move to the anode and the slower positive ions will drift towards the anode. The ratio of the total induced voltage from the electrons and ions as each drifts from the point of creation r_1 to the electrodes can be written as:

$$\frac{V^+}{V^-} = \left(\ln \frac{b}{(a + r_1)} \right) / \left(\ln \frac{(a + r_1)}{a} \right) \quad (5.8)$$

Now the amplification occurs only within a few wire radii from the anode because the $1/r$ fall off in the electric field with increasing radius, the avalanche is restricted to occur close

²This section taken from references: [90], [91]

to the anode wire. This effectively ensures that the gain will be constant, no matter where the ionization event has occurred because the kinetic energy gained by the drifting electrons will be considerably less than the ionization potential of the gas. Using values for the PCS proportional counter cartridge and assuming that the avalanche occurs 1 micron away from the anode wire, one finds that the contribution to the signal from the negative ions is only 1.5% of the positive ions. This allows us to essentially ignore the contribution by the drifting electrons and write the variation in pulse shape with time as:

$$\begin{aligned} V(t) &= \int_a^{r(t)} \frac{dV}{dr} dr \\ &= \frac{Q}{(2\pi\epsilon L)} \ln \frac{r(t)}{a} \end{aligned} \quad (5.9)$$

Now, $r(t)$ can be found from the equation of motion of a charge Q drifting along the field lines of an electric field $E(r)$. It has been found [92] that the drift velocity of positive ions are essentially proportional to the electric field:

$$\begin{aligned} v^+ &= \frac{dr}{dt} \\ &= \mu^+ E(r) \\ &= \mu^+ \frac{CV_0}{2\pi\epsilon r} \end{aligned} \quad (5.10)$$

where the proportionality constant μ^+ is known as the mobility of the gas. The equation above can be re-expressed as:

$$r dr = \mu \frac{CV_0}{2\pi\epsilon} dt \quad (5.11)$$

We can then integrate both sides of equation 5.11. One side of the equation is integrated from the minimum radius where the positive ions were created ($r=a$) to an arbitrary radius, and the

other side from 0 to a corresponding time t .

$$\int_a^r r dr = \mu^+ \frac{CV_0}{2\pi\epsilon r} \int_0^t t dt \quad (5.12)$$

This allows us to solve for the radius and evaluate the pulse shape as a function of time. From equation 5.9 we write:

$$\begin{aligned} V(t) &= \left(\frac{Q}{2\pi\epsilon L} \right) \ln \left(\frac{r(t)}{a} \right) \\ &= \left(\frac{Q}{4\pi\epsilon L} \right) \ln \left(1 + \frac{t}{t_0} \right) \end{aligned} \quad (5.13)$$

$$\text{where, } t_0 = \frac{a^2 \pi \epsilon}{\mu C V_0}$$

The output pulse for a beta in the PCS

The expression above is the case of a point ionization event. However, in the case of the PCS proportional counter cartridge, the pulse shape is more complicated since we have beta tracks travelling from the source on the wire outward, producing in the PCS approximately 98 electron- ion pairs /cm of gas. In this case we must also account for the drift of the electrons from the point of ionization to the anode where the avalanche occurs. Thus, if a track originates on the anode the primary electrons created closest to the wire will arrive first, create an avalanche, and due to the slow drift time of the positive ions created in the avalanche, induce a signal. Then, the next primary electron arrives and the output pulse is the superposition of the drift of ions from the first primary electron and the start of the second. For all subsequent primary electrons, the same situation applies until all the primary electrons drift toward the anode. In this way the total output pulse to a beta in the PCS will be the superposition of N primary electron avalanches, corrected for the time delays due to the time it takes for the primary

electrons to drift toward the anode.

5.3 Simulation of the PCS beta tracks

The output pulse due to beta particles in the PCS can be easily simulated (and thus understood) in a simple way provided that the following assumptions hold:

The beta tracks are straight This assumption holds as long as there is no hard angle scatters. This has been investigated with the EGS4 electron-gamma simulation code, where the initial direction of a simulated beta particle is compared to the exit angle out of a slab of argon gas. It was found that the multiple scattering in the gas was negligible, and that this assumption holds for most of the beta events seen in the PCS.

Ionization clusters for sizes of 3 or more electrons are not common In the simulation when a beta particle is emitted isotropically from the source on the anode wire in the PCS, the energy lost in the counter is calculated using the Bethe-Bloch formula. It is found that the energy loss in the gas is independent of the initial beta energy. The determination of the number of ion-pairs is calculated by dividing the most probable energy loss by the energy required to form an electron-ion pair. This also takes into account the fraction of secondary electrons which further ionize the gas. This is however, a Poisson process in the sense that the primary ionization electron scatters are independent events. Therefore, there is a chance that during the primary ionization interaction the beta will transfer enough energy to ionize additional atoms. In this way 'ionization clusters' may form of $n > 2$ electrons. The probability of clusters forming during an interaction has been experimentally investigated [93] and the probability distribution as a function of the number of electrons is given in Figure 5.1 below. From the graph it is clear that 90% of the ionization interactions produce clusters with size less

Figure 5.1 : *Probability distribution of cluster formation in % as a function of cluster size in argon [93]*

than 6 electrons.

The primary electrons drift toward the anode along radial electric field lines This is true as long as there is no magnetic field acting on the charged particles, which cause the charged particles to have a component parallel to the wire.

The energy loss in the gas is independent of the energy of the beta Using these assumptions, the pulse shape can be simulated. In the case of the PCS the energy losses in the P10 gas and thus the number ionization pairs is proportional to track length through the gas. This means that the pulse amplitude is directly proportional to the track length. The pulse shape for a typical beta track is shown in Figure 5.2.

Figure 5.2 : *Simulated pulse shape for beta tracks at varying angles to the anode wire. Not included in the calculation is the variation in the pulse shape due to the electronics.*

5.4 The PCS Design

The PCS is made up of a proportional counter in the form of a cartridge (PC), a polycarbonate container (PCC) that houses the cartridge, a stainless steel support structure (SS), a filling system (FS), a pressure sensor (PM), a preamplifier and a HV supply system (PA), a cover to protect the last three of the systems from the water and provide the attachment of the PCS to the positioning system and a monitor module (MANIM,PPNIM) which houses the electronic equipment to power and monitor the PA and monitor the operation of the system. See Figure 5.3 for a sketch of the assembled system. The important design criteria for each of these systems is described below.³

5.4.1 The Proportional Counter Cartridge

The proportional counter cartridge is an independent cylindrical cartridge 5 mm radius with thin walls of $\sim 50\mu$ opaque carbon loaded kapton (see figure 5.4). The Kapton is aluminized on the side facing the anode wire with a 800-1000 Angstrom coating, providing the cathode. The impedance on the outside of the cartridge is ~ 1 Mohm/square and provides shielding against microphonics and other noise. The ends of the cartridge are plugged with two end caps of black delrin that support the central wire. The end caps have a re-entrant design to increase the path from high voltage to ground. These end caps are opaque, and the unit is designed to prevent light from the proportional discharge escaping the cartridge. The carbon loaded kapton is glued to the end caps using low outgassing Scotchcast™. The anode wire is a 25μ m Stainless Steel wire tensioned (18 N) between the two end caps, and crimped to two CERN 100μ m feed-throughs. The following aspects of the design have been specially incorporated to limit the probability of the radioactivity escaping from the counter:

³This section is largely based on Report [94].

Figure 5.3 : *Diagram of the PCS assembly showing the acronyms used in the text for various components out of which the PCS is constructed.*

Figure 5.4 : *Diagram of typical PCS cartridge and table of cartridge components. Note that the numbers in the table correspond to components in the figure.*

- Gas access to the cartridge is only through one 1 mm hole in the top end cap.
- ^{228}Th is electroplated onto the central 3 mm of the wire.
- The cartridge is assembled in a separate room away from the rest of the PCS

The long insert that supports the cartridge has 2 grooves along the axis of the insert. The grooves support two 22 gauge wires which are glued to the kapton and provide the cathode ground. Both wires have been soldered to a standard gold coated PCB connector pin. The CERN 100 μm feedthrough is secured in place, by a drop of ScotchcastTM (Vinylcyclohexanedioxide). A PCB connector pin is glued to the feedthrough and provides the high voltage connection to the insulated wire that connects to the umbilical. There is an additional delrin washer which holds the feedthrough in place and prevents it from moving. The washer fits over the feedthrough and is fastened to the cartridge by means of 2 nylon screws.

Electrodeposition of ^{228}Th on Wire

In the course of this study, many different techniques of depositing ^{228}Th onto the anode wires were investigated. Techniques like vapour deposition, atomization, electro-spraying were studied but considered to be too time consuming to bring to fruition on our time scale. Consequently, M. Yeh of Brookhaven National Laboratory has assisted us to produce electroplated ^{228}Th coatings on anode wires. Electro-deposition is the technique commonly used to make good quality α -particle counting sources. The sources are approximately ~ 3 mm in length on the wire and are assembled in the cartridge so that the source is at the center of the active volume of the PCS. Approximately 90% of ^{228}Th in the solution is deposited on the wire. The Platinum dissolved from the electroplating anode forms a thin coating onto the wire to hold the ^{228}Th and its daughters in place on the wire. Initially a small amount of Platinum was added to the electrolyte to increase the retention of ^{228}Th on the wire. However, it was determined in analyses done with a Scanning Electron Microscope that the coating on the $20\text{-}25\mu$ anode wires had coatings of 10μ Platinum, which significantly decreased the proportional gain on the wire at the site of the electrodeposition (see Figure 6.5).

Studies with ^{55}Fe sources (see Chapter 6) reveal that with some sources there is a change in the gain near the site of the electroplated source. This occurs because the electroplating causes a thickening of the wire at the site of the source causing a variation of the gain (see Figure 5.5). Therefore finally no additional dissolved platinum is used in the final production of the ^{228}Th -coated wire. Unfortunately, using the Scanning Electron Microscope damages the anode wires and can only be done on anode wires that are no longer useful. Consequently, a shadowgraph ⁴ is used to scan along the wire to determine the thickness of the wire. Current sources have wire diameters that increase at most 5 micron at the position of the Th source.

⁴A shadowgraph is a device which allows the optical measurement of object no smaller than 1 micron. The device works on the principle of using the shadow produced by an object from a known distance light source to magnify and calibrate the image.

Figure 5.5 : *Pictures taken with a Scanning Electron Microscope showing a view of a uncoated (top) and Th/Pt coated (bottom) wire. Clearly visible is the increased diameter of the coated wire as compared to the uncoated wire, decreasing the gain near the position of the source*

Cartridge	^{228}Th Activity
PCA	$191 \pm 5\%$ Bq
PCB	$90 \pm 10\%$ Bq
PCD	$1000 \pm 10\%$ Bq
PCE	$1500 \pm 10\%$ Bq
PCF	$40 \pm 10\%$ Bq

Table 5.1 : *Various PCS source cartridges used in this study and their measured ^{228}Th activities*

PCS Source Cartridges

In the process of this study several PCS ^{228}Th cartridges (see Table 5.1) have been made for use by SNO. One source cartridge labelled *PCA* has a measured activity $191 \pm 5\%$. The measurements on this source will be described in detail in Chapter 6. Note that all of the sources above have ^{228}Th as their active isotope.

Recommendation for Qualification of a PCS Cartridge

As part of the Quality Control and Quality Assurance to be discussed, it is recommended that the following tests are performed for qualifying a PCS source prior to deployment:

- Cartridge components are cleaned according to the regular cleaning procedure ⁵
- A wire scan is done with a shadowgraph to determine the width of the Th coating along the wire.
- A leach check for ^{228}Th is done on the anode wire prior to mounting the wire
- Continuity is checked of the anode and ground wires
- The mechanical strength of the CERN feedthrough is inspected

⁵Note cleaning procedure is not included in this thesis but can be found on the PCS website www.physics.carleton.ca/snoman/

Figure 5.6 : *Diagram of a typical polycarbonate housing (PCC) showing the 12° cones on each side. The wall of the PCC cylinder in the active area of the proportional counter cartridge is 0.7 ± 0.1 mm thick*

5.4.2 The Polycarbonate Housing (PCC)

The cartridge (see Figure 5.4) is loaded in the polycarbonate housing (PCC) which consists of a thin walled cylinder with two 12° cones on each side pointing back to where the source is (see Figure 5.6). In this geometry we expect $\sim 4\%$ of particle tracks to hit the end cap. Over the central region of the PCC the wall is 0.7 ± 0.1 mm to allow the escape of the beta's and γ -rays from the source with minimum energy loss to the particles. The ends are cone-shaped to add strength and such that they will intercept little radiation. One end of the tube is closed, and the other is attached to a stainless steel pipe connected to the rest of the PCS assembly. The PCC is sealed with double o-rings seals onto the SS pipe. Polycarbonate is chosen as a material as it fails in a ductile manner. Tests to failure conducted and described in proceeding sections confirm that the ductile mode is the failure behaviour. The margin of safety for the polycarbonate component under the most extreme condition (PCS at vacuum, deployed at the bottom of PSUP) is 3.9.

5.4.3 Stainless Steel Assembly (SS)

The Stainless Steel Assembly (labelled SS on Figure 5.3) is composed of a pipe which is attached to a stainless steel can. The function of the pipe is to place the can of the PCS in the

shadow of the 12 degree cone of the polycarbonate component. The assemblies purpose is to provide a water-tight enclosure in which to place the PCS electronics (pre-amp (PA), pressure monitor (PM), Fisher electronic high voltage (HV) connectors) and the gas filling system (FS). The assembly also provides a gas-tight housing for the P10 (90% Ar/10% CH₄) fill gas which can pass readily through the one mm diameter hole in the cartridge. The entire PCS assembly is shown in Figure 5.3. A CERN 10kV cable carries the HV and signal through the center of the Stainless Steel pipe to and from the cartridge. One end of the 10 kV cable connects to a locking-clip and is permanently enclosed in a plastic housing. The PCB pin that is soldered onto the CERN feedthrough then mates directly to the locking clip housing. The fit is blind, and can be removed with little force. Similarly, there is a single non-insulated ground wire which spirals around the CERN 10 kV cable and connects to the two grounding leads on the cartridge. On the other end of the CERN 10kV cable, the cable anode is soldered onto the pin and the ground to the grounding lead of a hermetically sealed W.W.Fisher connector. This is the feed-through of the HV and signal from the pre-amp to the proportional counter cartridge. The connector is hermetically sealed because the counting gas (P10) fills the volume from the HV feedthrough to the cartridge. In order to add additional safety against the escape of the radioactivity, all the seals in the stainless steel assembly are double O-ringed except for the HV feed through and where the pressure monitor is attached. Once the PCS is deployed a single o-ring seal stainless steel cover (labelled 'cover' in Figure 5.3) fits over the electronics and filling system and provides a water-proof barrier.

Pre-Amplifier (PA)

The pre-amplifier (labelled PA on Figure 5.3) is custom made and is charge sensitive. The pre-amp mounts directly into the receptacle of the hermetic Fisher HV connector through a second panel mount connector. There is an added support in the form of a set-screw which clamps the panel mount connector on the pre-amp to the HV hermetic connector. In this way the pre-

amp does not have freedom to move. On the other end of the pre-amp the pre-amp takes the High Voltage from the umbilical through a filter network to a non-latching W.W.Fischer HV connector. This connector then mates to a HV connector mounted on the pre-amp. The input and output circuits of the pre-amp are both protected by diode circuits. A test pulse from a pulse generator is provided to the pre-amp for test purposes, and is sent into the input through a 2.2 pF capacitor. The low voltage power to the pre-amp and pressure monitor (± 12 V) are conveyed through the umbilical. The ground is supplied to the circuit board by the ground on the cable from the pulse generator and the HV cable. These lines are well decoupled to prevent pickup. The output from the proportional counter cartridge is coupled to the HV coaxial cable and sent through the umbilical to the electronics on the deck. A schematic of the PA is shown in Appendix B.

The Pressure Monitor (PM)

The pressure sensor (labelled PM on Figure 5.3) is a rugged, miniature Titanium flush membrane pressure transducer. The signal from the sensor is 0-100 mV for a pressure change of 150 psia. The output is from a Wheatstone bridge circuit and sent on two separate umbilical lines to the deck. The pressure transducer is screwed in by M5 thread into a stainless steel cylinder that has a 1/4" pipe thread. The sensor is sealed to the cylinder by a stainless steel/nitrile gasket. The cylinder is screwed into a boss welded onto the top plate of the SS with 1/4" pipe thread. The sensor is powered from the same low voltage supply lines as pre-amp. Its signal lines are protected to prevent HV discharges from damaging the circuits on the monitors.

Filling and Gas System (FS)

The PCS requires the counter gas fill to be evacuated and re-filled on a short term basis. The PCS filling system (see FS on Figure 5.3) is composed of three stainless steel pieces: two valves

and a Swagelokquick connect. The quick connect allows the FS to be attached and detached from the gas supply, and to be evacuated without swaging. In this way it is not necessary to torque the connector when filling or evacuating, which adds uncertainty to the integrity of the gas seal. The three pieces that make up the FS are welded together and welded to the SS assembly. In order to protect the system from releasing radioactivity this system has the following safeguards.

- In operating mode the gas is double sealed by two valves and has the third seal of the quick connect.
- The system is interlocked (see Figure 5.3) to prevent the quick connect from being released without the nearest valve being closed. This effectively removes the possibility of the PCS accidentally releasing pressure, or to be disconnected with the valve open.

5.4.4 Umbilical

The umbilical ⁶ is a flexible tube that provides the electrical connections from the deck to the PCS. The PCS umbilical contains a central RG 59 coaxial cable, which provides the HV power to the PCS and carries the signal to the deck. Four 24 AWG insulated wires are helically wound around the central coax, providing the power (+12 V,-12 V) to the pre-amp. The wires also carry the signal from the pressure sensor to the deck. There is an additional RG 174 coaxial cable which provides a test input to the pre-amp for on-line diagnostics. The umbilical is constructed by running the required cables for the PCS through a clear heat shrink and through the center of a silicone tube. The entire tube is then placed in a 0.5" copper tube. The space between the tube and the heat shrink is injected with RTV silicone, which sets and makes the umbilical solid and the copper tube is removed.

On the PCS the umbilical passes through 3 pressure plates (circular plates with an O-ring

⁶The umbilicals are constructed at Queens' University by the team of B. Moffatt *et al*

sandwiched between each plate) mounted on the PCS cover to the electronics. A clamp is placed on the end of the umbilical to prevent the umbilical from slipping out of the aperture. The purpose of the pressure plate O-ring sandwich is to provide a water-tight seal with the PCS and to have an additional support for the PCS, in case the umbilical retrieval mechanism's ropes fail.

5.4.5 The PCS NIM Modules

MANIM Module

The MANIM (Monitor and Alarms Module) is a NIM module which supplies the power to the pre-amp and the pressure transducer. It also includes 3 alarms for pressure loss (adjustable but set at 2% drop in pressure), rate change, and HV trips (current exceeds 80 nA). These are wired into the SNO Controls Monitors and Alarms system, which is a central computer which monitors and records SNO's environmental conditions and issues alarms if necessary. The rate meter circuit is sensitive to changes in the pressure since the gain on a proportional wire is an exponential function of pressure. Thus this is a method of verifying there is no breach in the seal independent of relying on the output from the pressure sensor. Each of the 3 alarms (Pressure, Voltage trip, Rate) are all individually connected to LEDs which allows the operator to know which alarms have been activated in the case there is a failure. The LEDs are used to diagnose the seriousness of the failure condition should the PCS malfunction. This is described in more detail in Chapter 7. See Figure B.2 in the Appendix B for the schematics of the MANIM module.

PPNIM Module

The primary purpose of the PPNIM (Pulse Processing Module) module is to decouple the PCS signal from the DC HV by using a blocking capacitor. The PCS signal is processed in the

module to produce three outputs:

- Buffered Output: Shaped Pulse used as input into amplifier
- Shaping Output: Inverted pulse used as input into NIM modules such as discriminator
- Direct Output: Pulse immediately after HV is stripped. Pulse used for diagnostics with an oscilloscope

See Figure B.3 in the Appendix for the schematics for the PPNIM module.

5.5 PCS Mechanical Testing

5.5.1 Hydrostatic Pressure Tests

In order to confirm that the design of the PCS is safe and will not compromise the SNO experiment, hydrostatic pressure tests were performed. The entire PCS assembly is hydrostatically tested with particular attention to the PCC, since the only barrier between the PCS cartridge and the D_2O is 0.7 mm of polycarbonate. The PCC is the most vulnerable aspect of the design and its integrity must be rigorously tested.

For this reason, five PCC's were hydrostatically tested with an internal pressure of 1000 psi. The maximum pressure was maintained for 30 seconds, and no damage was observed. The outside diameter of one tube was measured before and after the test to confirm that no plastic deformation had taken place. The failure pressure was calculated to be 1340 psia. One chamber was hydrostatically tested with an external pressure and failed at 340 psia. This should be compared to the engineering handbook calculation for buckling of a thin walled polycarbonate cylinder of 177 psia [95]. The Young's Modulus was assumed to be 300k psi. One of the reasons for the higher value may have been that the test took place over a short period of time ~ 2 minutes (with pressure increments about every 5 seconds) and at lower temperature (~ 12 degrees C) so a higher Young's modulus should have been used.

Tests were also conducted when the pressure was increased in steps of 25 psi in longer time increments (10 minutes), and at a lower temperature of 5° Celsius. Several external pressure tests were done to failure. Two polycarbonate piece failed at 235 psia and another failed at 265 psia. An additional piece was ultrasonically cleaned for 6 times the suggested time according to the PCS cleaning procedure to ensure that the cleaning procedure does not have an adverse effect on the polycarbonate. This piece failed at 290 psia. There were also internal pressure tests (6) to ~1000 psia, but none were conducted to failure.

In all cases the cylinders failed plastically, collapsing along its length. No cracks were observed and no leaks were detected. The polycarbonate showed some whitening along the line where the cylinder had bent the most. After the external pressure tests (buckling) of the pieces, the cylinders were pressure tested again to 1000 psi. It held this pressure without any leaks, though it was still slightly oval after this pressure test. The fully assembled PCS has also been proof tested to an external pressure of 125 psia to verify the integrity of the assembly. No evidence of damage was observed.

5.5.2 Effect of Chamber Gas

In order to ensure that the P10 (90% Ar/10% CH₄) gas does not have a detrimental effect on the polycarbonate, a test was conducted using one of the test cylinders. The polycarbonate component was filled with 100 psia of methane over 9 months. In summary there does not seem to be a degenerative effect of methane on polycarbonate. After a long period of exposure to methane, the PCC was pressurized internally to 1000 psia for 5 minutes and no failure was observed.

5.5.3 PCS Drop Tests

Tests were conducted, where a larger diameter stainless steel prototype of the PCS was dropped at different angles and velocities onto a stainless steel slab. The PCS was dropped vertically (so that the angle between the stainless steel plate and the central axis of the PCS is 90 degrees) at constant speeds of 3 cm/sec, 5cm/sec and 8.3 cm/sec. The rest of the PCS was allowed to fall so that most of the weight is supported by the polycarbonate piece. The polycarbonate component was observed to maintain the integrity of its walls and seemed (although not visually confirmed) to act slightly as a 'spring' when lifted. The same test was done repeatedly where the stainless steel plate was varied to 84 degrees (3 times), 80 degrees (3 times) and 75 (3 times) degrees. The polycarbonate slid along the stainless steel plate scraping some of the polycarbonate onto the stainless steel plate. In this case the end of the polycarbonate is allowed to move and rub against the stainless steel plate. This simulated the PCS upon deployment experiencing friction against a rigid surface and being forced to slide along it.

Repeated tests were done where this time a buffer is placed at the end of the stainless steel plate. This will prevent the polycarbonate from skidding along the surface of the stainless steel plate. This was done for the same angles as above for the same number of times. This simulates the PCS getting stuck because of a feature/recess in the guide tube through which it is deployed. By lowering the PCS and constraining the end of the polycarbonate, all of the weight is placed on the polycarbonate. It was observed that the polycarbonate bent slightly under the force and when lightly tapped the vibration could be felt along the polycarbonate wall.

All these tests were conducted with speeds greater or exceeding 3 cm/sec, the typical speed that calibration sources are deployed. Therefore these tests are overestimating the speed at impact if a calibration source collides with an object. After these tests were completed the polycarbonate component used was hydrostatically tested internally to 1000 psi to verify that

the thin 0.7 mm wall was not damaged. These tests suggest that the polycarbonate component under sudden impact deforms, rather than shattering as we have observed earlier in hydrostatic pressure tests.

5.6 Quality Control and Assurance

5.6.1 Quality Control

Quality control (QC) describes the protocol that ensures that the construction, handling, deployment of the source is done in a manner that will not compromise the SNO experiment. This was legitimized through the use of many procedures, which ensure that there is no cross-contamination during cleaning and handling.

5.6.2 Quality Assurance

Quality Assurance (QA) describes the independent tests that are done to verify that if there is a breach in the QC protocol the QA tests will detect it. QC describes methods to decrease the amount of ^{228}Th cross-contamination, while QA techniques are in place to determine the ^{228}Th content in various components of the PCS. The crucial unit in which to express the ^{228}Th contamination is the number of extra neutrons that would be produced by photodisintegration of the deuteron. As discussed in Chapter 4, approximately one in 482 ^{208}Tl 2.6 MeV γ -rays will produce a free neutron [69] which is a background to the neutral current measurement. For this reason the result of the various ^{228}Th assays are expressed in terms of the number of extra neutrons produced in SNO, if the various components were accidentally deposited in the SNO active volume.

Leaching Tests

A pre-requisite for PCS deployment is a leaching of the entire PCS assembly in UPW with the subsequent assay of the ^{228}Th content in the leachate. The PCS is leached so that the middle flange (the flange that the FS is welded to), HV connector and FS are exposed to UPW. The pressure transducer is masked off using a plastic adapter sealed with an o-ring. So that this is an external and an internal leaching of the PCS source. The PCS is left submersed in UPW and for at least 3 days at room temperature. It should be noted that prior to the leaching, the PCS is pressurized internally to 51 psia. Which means that the leach test is measuring not only the leaching of ^{228}Th from surface contamination of the PCS, but it is also measuring whether any ^{228}Th is coming out of the PCS with an internal pressure differential of about 36 psi. When the PCS is deployed in SNO, the PCS internal pressure is always 51 psia to ensure that wherever the PCS is deployed it will never be under compression. If the PCS is deployed at the center, the relative pressure with respect to the D_2O of the PCS is about 14 psi. This should be compared to a 36 psi pressure differential for the leaching test. Thus, a leaching test when the PCS is internally pressurized is a good test not only for measuring the surface contamination, but also for determining whether any ^{228}Th is coming out of the PCS into the water. Furthermore, the leaching is performed in UPW at room temperature, which is at least 10° higher than the temperature of the D_2O and H_2O in SNO. If we assume that every 10° increase in leachate temperature doubles the effective time for the leaching test, then we have leached for a time exceeding 6 days of run time in SNO.

The water is then processed in several ways. One method is to reduce the leachate to a smaller volume and electroplate the Radium out of the leachate [96]. This and other methods have been used at Brookhaven National Laboratory and at Carleton University to assay the PCS leachate. However, the default method is to use the liquid scintillation counter (described in chapter 4) to assay the amount of ^{224}Ra in the water. The latest source assayed demonstrated

Figure 5.7 : *Diagram of set-up of PCS depressurization test to assay ^{228}Th present in the PCS gas.*

a ^{224}Ra lower limit of 0.8 ± 0.69 decays per hour. This corresponds to a 1σ limit of 1 photo-disintegration neutron every 40 days, compared to a neutral current signal of ~ 10 neutrons per day.

5.6.3 description of tests when PCS gas is vented to atmosphere

We have completed a series of tests to determine the ^{228}Th activity present in the PCS gas. This should be part of the regular qualification of a PCS source. The PCS was filled with P10 to 50 Psia and then depressurized through a 0.2 micron filter to atmosphere (see Figure 5.7 below). The filter assembly was composed of a 0.2 micron filter sandwiched between 2 male quick connects that can be connected directly to the female quick connect on the PCS. The gas was then released to atmosphere by pressing on the exposed tip on the quick connect. This process of filling with P10 and de-pressurizing to atmosphere through a 0.2 micron filter was done 100 times. The filter was then removed from the filter holder and mounted on a planchet to be counted in a low background alpha counter.

^{228}Th decays to ^{224}Ra with the emission of 5.43 MeV (72.6%) and 5.34 MeV (27.4%) α -particle, however, these α -particles cannot be distinguished from the much higher amplitude tail of the ^{222}Rn alpha at 5.49 MeV from the U-chain. Thus ^{228}Th decay cannot be directly

used to put a limit on the amount of ^{228}Th on the filter. Rather the decay of the ^{228}Th daughter ^{224}Ra is used, since it decays by emitting a 5.68 MeV α -particle with negligible interference from tails of other alpha peaks. ^{224}Ra decays to short-lived (56 s) ^{220}Rn whose daughters emit 6.29 MeV and 6.78 MeV α particles (see Figure 4.1). However, these α -particles also cannot be used to determine the amount of ^{228}Th on the filter because it is not clear how much Rn may have escaped the α particle detector. The alpha counter was calibrated using an ^{241}Am standard and using an electroplated ^{226}Ra source (showing 4 clear alpha peaks ranging from 5.3-7.7 MeV). A 100 keV region of interest was placed around the ^{224}Ra alpha peak and was counted over several days.

Analysis

A formula can be worked out to calculate the amount of ^{224}Ra decays we expect from ^{228}Th and ^{224}Ra on the filter throughout the counting process. We start with the activity as a function of time for the ^{228}Th and ^{224}Ra isotopes.

$$dN(\text{Th}, t)/dt = -\lambda(\text{Th}) \cdot N(\text{Th}) = -R \quad (5.14)$$

$$dN(\text{Ra}, t)/dt = \lambda(\text{Th}) \cdot N(\text{Th}) - \lambda(\text{Ra}) \cdot N(\text{Ra}, t) \quad (5.15)$$

$$= R - \lambda(\text{Ra}) \cdot N(\text{Ra}, t) \quad (5.16)$$

Where, $N(\text{Th}, t)$ is the amount of ^{228}Th ($T_{1/2}=1.9$ y) atoms on the filter and $N(\text{Ra}, t)$ is the number of atoms of ^{224}Ra ($T_{1/2}=3.66$ d) that is growing in on the filter as a function of time. $\lambda(\text{Th})$ and $\lambda(\text{Ra})$ correspond to the decay constants of ^{228}Th and ^{224}Ra respectively. These equations can be solved to obtain the amount of Ra present on the planchet. In the case of ^{228}Th we can assume that $\lambda(\text{Th}) \ll \lambda(\text{Ra})$ and since we are interested in the contribution of ^{224}Ra from the ^{228}Th we neglect the full solution which includes the amount of ^{224}Ra initially on the filter. We have another motivation for neglecting the contribution from ^{224}Ra initially

on the filter, because we will get a more conservative estimate of the amount of ^{228}Th when we neglect the contribution from the number of atoms of ^{224}Ra on the filter at the start of the counting period. Solving these equations we get that the number of Ra atoms on the filter as a function of time is given by:

$$N(Ra, t) = \frac{R}{\lambda(Ra)} \cdot (1 - e^{(-\lambda(Ra)t)}) \quad (5.17)$$

However, to get the number of ^{224}Ra atoms that have actually decayed in a time t , we must subtract the number of Ra atoms that would have been produced without decaying in the same time period. In other words:

$$N(Ra, t) + (\# \text{ of decays during time } t) = (\# \text{ of Ra atoms produced in time } t)$$

Therefore, the number of ^{224}Ra decays ($N_{dec}(Ra, t1, t2)$) due to presence of ^{228}Th for counting from $t1$ to $t2$ is:

$$\begin{aligned} N_{dec}(Ra, t1, t2) &= R \cdot [(t2 - t1) - (N(Ra, t2) - N(Ra, t1))] \\ &= R \cdot [(t2 - t1) - (1/\lambda(Ra)) \cdot (e^{-\lambda(Ra)t1} - e^{-\lambda(Ra)t2})] \end{aligned} \quad (5.18)$$

So that the number of ^{228}Th atoms on the filter at the start of counting (ie. at $t1$) is:

$$N(Th) = \frac{N_{dec}(Ra, t1, t2)}{[(t2 - t1) - (1/\lambda(Ra)) \cdot (e^{-\lambda(Ra)t1} - e^{-\lambda(Ra)t2})] \lambda(Th)} \quad (5.19)$$

Results

The filter exposed to the PCS gas was mounted on a planchette and counted in an α -particle counter. After 3.66 days 18 counts in the ^{224}Ra region of interest are obtained. We have also measured the background in the ^{224}Ra region of interest of a blank filter and measured it to be 3.6 ± 2.5 decays per day. So that for 3.66 days of counting, the background subtracted number

of decays in the ^{224}Ra region of interest is consistent with 5 ± 4.9 decays. If we assume this is all due to ^{228}Th decay and applying equation 5.19 the number of ^{228}Th atoms on the filter is $4.6\text{k} \pm 4.5\text{k}$ ^{228}Th atoms.

However in both analysis, we have not included the counting efficiency nor have we included the efficiency for the transport/trapping of ^{228}Th onto the filter. We make the following simple argument. If we assume that the efficiency is small for the transport/trapping of ^{228}Th particulate onto the filter, the fact that we do it 100 times, will make this efficiency negligible. Lets say we have N ^{228}Th atoms in the counter and each time the gas is discharged out of the counter through the filter we trap the ^{228}Th atoms with an efficiency ε . then if we do this experiment t times then the number of atoms trapped on the filter is:

$$N_{trapped} = \varepsilon * N * [1 + (1 - \varepsilon) + (1 - \varepsilon)^2 + (1 - \varepsilon)^3 + \dots + (1 - \varepsilon)^{100}] \quad (5.20)$$

If t was large then we get the sum of a geometric series:

$$N_{trapped} = \varepsilon * N * (1/\varepsilon) = N \quad (5.21)$$

In particular if $\varepsilon=3\%$ for 100 gas pressurizing/de-pressurizing cycles we still recover 95% of the atoms in the gas. So since we are doing this experiment many times the transport/trapping efficiency is assumed to be 1 in the calculation of the number of ^{228}Th atoms on the filter.

The counting efficiency is determined by a Monte Carlo of the alpha counter geometry (see Figure 5.8). Alpha particle tracks are simulated for a circular filter assumed to be uniformly coated with the α -particle source. The position of the origin of the alpha tracks are uniformly distributed on the filter and the direction of the track is assumed to be isotropic. The track direction is extended to the ridge (at $Z=2$ mm) and it is determined what radius the α -particle is from the Z -axis. If the α -particle at $Z=2\text{mm}$ has a radius exceeding the radius of the alpha

Alpha Counter Geometry Assumed in MC:

- Diagram showing uniformly coated planchet. Alpha track 1 is not detected. Alpha track 2 is considered to be detected.

Figure 5.8 : *Diagram of monte carlo assumed alpha counter geometry*

counter the event is rejected. If the α -particle at $Z=2\text{mm}$ is within the alpha counter active radius, then the alpha track is extended further in the same direction to determine if the α -particle will hit the alpha counter active area. The alpha counter efficiency for the filter counting geometry is calculated in this way to be 21.6%. Therefore using this efficiency a conservative estimate on the amount of ^{228}Th atoms on the filter from run 3 is $21.9\text{k} \pm 21.5\text{k}$ ^{228}Th atoms.

Conclusions: Consequences of Measured Gas Release:

If we assume that all of the ^{228}Th is released directly into the SNO active volume, the ^{228}Th decay rate would be at most 22 ± 21 ^{228}Th decays per day. This is equivalent to 1 additional ^{208}Tl neutron producing a neutral current background in SNO, every 60 days. This is an important result because it demonstrates that while the PCS cartridge may cause contamination if accidentally deposited in the SNO active volume, the PCS gas will not.

5.6.4 Post-Mortem of PCS Cartridges

Leach Test of a PCS Cartridge

The 'PCB' ^{228}Th cartridge (see Table 5.1) is placed in a test tube filled with 25 mL water and then injected with UPW through the gas hole in the cartridge. After 48 hours, the water exterior to the cartridge was removed and the Radium (^{224}Ra daughter of ^{228}Th) electroplated onto a planchet. The electroplating efficiency is determined by electroplating the Radium in an identical volume UPW to which a known amount of ^{226}Ra is added. Both planchettes (one from the Ra tracer and one from the pure leaching sample) are then counted in an alpha counter. Since we have used Radium as a tracer we are interested in the integrated number of counts in the peaks of ^{226}Ra (for the tracer sample) and ^{224}Ra for both planchettes. By comparing the number of counts in the ^{226}Ra peak to the known amount of ^{226}Ra that was put into the volume of water we can trace the efficiency of the reducing/plating technique. Using this technique we determine the reduction/plating efficiency to be (0.16 ± 0.024) . Furthermore we have determined the efficiency of the alpha counter to be 0.2 using a calibrated ^{241}Am source. Therefore, the number of counts observed in the ^{224}Ra peak in the leaching sample should be multiplied by a factor of $31 \pm 15\%$.

For the leaching sample of UPW External to the cartridge, we get 100 counts in the ^{224}Ra peak per day, which taking into account the Ra that has decayed during the counting amounts to 107 counts per day initially. If we multiply this by the efficiency factor we get 3317 ^{224}Ra decays per day for a period of 2 day leaching. This is equivalent to 2.3 photodisintegration neutrons of additional background to the neutral current per day. This is a significant amount of contamination with respect to the NC signal in SNO, and must not be understated. However, in terms of the fraction of the total activity of the ^{228}Th source, only 0.05% of the source has entered leachate, indicating that the ^{228}Th source is adhering to the wire.

Alpha Counting of Carbon Loaded Kapton (CLK) cathode

We have also dissected our most active PCS cartridge (1500 Hz) and measured the activity of the CLK with an alpha counter. The cathode was cut into 4 strips vertical to the cathode so that strip 2 and 3 correspond to the strips closest to the source. There was no difference in the rate of the ^{228}Th peak for the central strips. For each strip the exposed area to the alpha counter is $\sim 190 \text{ mm}^2$. The 1σ upper limit placed on the ^{228}Th activity on the strips is $< 0.001 \text{ Bq}$. If we assume a cathode area of $\sim 30 \times 50 \text{ mm}^2 = 1500 \text{ mm}^2$. Then a limit on the total activity on the cathode is $\sim 0.008 \text{ Bq}$. Therefore, the upper limit on the fraction of ^{228}Th that has left the wire is 0.0005% .

5.7 Safety Considerations

As mentioned, the first criterion for PCS design and a prerequisite to deployment, is that the PCS will not compromise the integrity of the SNO detector. In this section we list the precautions built into the PCS in order to guarantee its safe deployment in SNO as well as describe some additional safety measures. The major concern we address here is the danger of the thorium on the anode wire leaking into the water.

1. All critical o-ring seals are doubled.
2. The radioactivity is contained in its own cartridge with only a small (1 mm) hole for filling and evacuating the charging gas.
3. The radioactivity is electroplated onto the wire. This makes it entirely solid matter. Rate measurements and searches for thorium daughters on the walls give no evidence of the thorium leaving the wire. These tests are at the level of a few percent. The pressurized counter has been de-pressurized from its operating pressure to atmospheric pressure by

100 sudden releases through a .2 micron filter. No evidence of ^{228}Th was found on the filter with limits at a few counts.

4. The SS has been tested to 1000 psig internal and 350 psig external pressures. The operating pressure is 50 psia.
5. The operating pressure is such that the pressure difference across the PCC is small.
6. The assembly has been drop tested well beyond the danger level in SNO.
7. The filling and evacuation system has been double protected against any activity getting out of the source with two valves and a quick connect. This system has a fail-safe protection built into it in order to prevent the quick connect from being disconnected without closing the valve.
8. The alarm system of the High voltage supply is connected to a sonic alarm and to the CMA system to warn us of any loss of high voltage for any reason.
9. The output of the PM is connected to an alarm system that sounds a sonic alert and triggers a CMA alert if there is a drop in pressure in the PCS.
10. There is an alarm system that monitors the rate from the counter. Any drop in pressure will cause the rate to rise and this will trigger the alarm.
11. The source has been run at the temperature of ice water over night to make certain that there is no deleterious effect from its insertion in the SNO water.
12. It has been run sealed in water of a period of 1 week in order make sure there are no unexpected effects of water on the operation of the counter.
13. The system will be evacuated/filled at Carleton University and then sealed and taken underground. It will only be handled at Carleton University.

Chapter 6

Proof of Principle

6.1 Introduction

In this chapter the criteria for PCS design are described in an effort to convince the reader that these issues have been successfully dealt with. To remind the reader the 5 design criteria listed in Chapter 4 are:

- [1] PCS cannot pose a risk to SNO
- [2] PCS ^{228}Th source activity must be a well known constant
- [3] PCS can be triggered or tagged so that its contribution can be identified with respect to the rest of the triggers.
- [4] PCS position must be well determined in SNO
- [5] PCS must closely approximate a ^{228}Th point source

The main purpose of Chapter 5 is to convince the reader that the PCS will not compromise the physics in SNO (point 1 above), in this chapter we deal with all the other criteria for the PCS design.

6.2 PCS ^{228}Th source activity must be a well known constant

The PCS is essentially self-calibrating. This is because all of the event classifications described below must be proportional to the ^{228}Th activity of the source. This implies that all the rates from all the various event classifications must be self-consistent. This self-consistency allows various tests to be performed to extract the ^{228}Th activity of the cartridge.

6.2.1 Events Seen from ^{228}Th Source

This section ¹ describes the response of the counter to ^{228}Th electroplated on a stainless steel 25-micron diameter wire at the center of the sensitive region (see Figure 5.4). The ^{228}Th chain emits five alpha particles and two beta particles on the way to stable ^{208}Pb . The abbreviated chain is shown in Figure 6.1.

To understand all the possible event classifications for ^{228}Th , it is necessary to consider what the pulse shape is from particles seen in the ^{228}Th chain. The particles emitted from this chain are betas, α -particles and γ -rays. The mean free path for γ -rays in the gas is very long so that γ -rays will not interact with the low density gas. However, as described in the previous chapter, the betas and α -particles will ionize the gas proportionally to the energy these particles deposit in the gas. The α -particle deposits approximately 3 orders of magnitude more energy in the gas so that these particles will produce many more ions in the gas and thus, the pulse height as calculated in the previous chapter of a beta will be a fraction of an alpha. Furthermore, since the beta deposits a fraction of its initial energy, its amplitude will be proportional to the track length and will not mimic the beta spectrum. In the case of the PCS the beta track length varies as the inverse sine of the angle the track makes with respect to the anode. For 3 atmosphere pressure, relativistic beta particles produce about 120 electrons in crossing the 5

¹The following sections are taken from [94]

Figure 6.1 : The ²²⁸Th Chain. Adapted from [97]

mm radius of the counter. At the minimum angle of 13° to the anode wire this increases by about a factor of 5 to about 600 electrons. This behaviour is shown in Figure 6.2 for a Monte Carlo calculation (see Chapter 5) of a ²¹²Bi beta emitted isotropically from a source on the anode wire. Included in this calculation is the Landau distribution ² for the energy loss in the gas and a resolution function taken from the ⁵⁵Fe peaks (see next section) to take into account gain straggling in the PCS. The initial rise is due to the minimum energy loss of a beta that is travelling radially outward. The gradual fall-off in the spectrum is due to the combination of the Landau distribution and the decreasing solid angle of longer track length betas.

The rise time of the pulses from the counter is about 150 ns, which is the electron drift time for electrons from the cathode to the wire. This rise time applies for all particles that travel to

²The Landau distribution is incorporated in the Monte Carlo using the stand alone program FLION [98] for the fluctuations in the energy loss

Figure 6.2 : *Monte Carlo calculation of the ^{212}Bi PCS Beta Spectrum*

the cathode wall of the counter. A simulated PCS cartridge pulse shape is shown in Figure 5.2 using the formula for the pulse shape derived in the previous chapter. For beta particles going into the end cap of the counter, the rise time will be proportional to the maximum radius reached by the particle and the amplitude will become approximately constant. The gain in the PCS is adjusted to be sensitive to the beta amplitude, such that the initial rise and gradual fall in the spectrum in Figure 6.2 can be seen.

The α -particles however, will deposit a large amount of energy ³ in the gas and saturate the electronics. For this reason we have constructed a logarithmic preamplifier to limit the pulse size. Its logarithmic response allows us to measure low amplitude beta particles in the presence of high amplitude α -particles.

³Some fraction of the α -particles may also be absorbed in the anode wire. This fraction is calculated and is an important variable in determining the activity

Event Classifications

For the understanding of the various event classifications, the important part of the ^{228}Th chain is from ^{212}Pb to ^{208}Pb . For this part of the chain the important particles in the PCS are the beta particles from the ^{212}Pb to ^{212}Bi transition, ^{212}Bi to ^{212}Po and ^{208}Tl to ^{212}Pb decays and the ^{212}Po α -particle decay. As mentioned before, ^{208}Tl is particularly important for SNO because of the ^{208}Tl to ^{208}Pb transition which produces one of the main backgrounds in SNO. We use the 300 ns half-life of the ^{212}Po α -particle decay to tag the $^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ part of the ^{228}Th decay chain. From the measurement of this part of the chain and knowing the ^{208}Tl branching fraction, we can quantify the $^{212}\text{Bi} \rightarrow ^{208}\text{Tl} \rightarrow ^{208}\text{Pb}$ branch. Thus, the signal observed in the proportional counter due to the 64% branch of the decay of ^{212}Bi is a low amplitude beta followed several hundred 10^{-9} s later by a high amplitude alpha saturating the preamplifier of the PCS. The low amplitude betas are selected by triggering on the Lower Level Discriminator (LLD) set at the lowest amplitude above the noise. The α -particles are selected by triggering the Upper Level Discriminator (ULD) set in the valley between the fall off in the pulse height spectrum from the betas and rise due to the α -particles. The LLD will trigger both from betas and α -particles observed in the PCS, whereas the α -particles will only trigger when a ULD fires. All the possible event classifications and their isotopes of sensitivity are shown in Table 6.1.

6.2.2 ^{55}Fe Tests

The quality of a proportional counter is often evaluated based on the pulse height spectrum obtained from a ^{55}Fe source. ^{55}Fe decays to ^{55}Mn by electron capture of a K-shell electron:

This process generates several possible X-rays in the Mn atom denoted as E_γ^{Mn} [99]:

Event Type Classification	Main Isotopes of Sensitivity and Particle Detected
LLD	^{212}Pb , ^{212}Bi , ^{208}Tl β 's and ^{228}Th , ^{224}Ra , ^{220}Rn , ^{216}Po , 36% ^{212}Bi α 's
LLD·ULD(delayed)	64% ^{212}Bi β 's
ULD	^{228}Th , ^{224}Ra , ^{220}Rn , ^{216}Po , 36% ^{212}Bi α 's
LLD·ULD(delayed)·Scintillator	64% ^{212}Bi β 's
LLD·Scintillator	^{212}Bi β 's
Scintillator·ULD(delayed)	64% ^{212}Bi β 's
Scintillator·ULD(delayed)·LLD	64% ^{212}Bi β 's

Table 6.1 : *Summary of the event types and how these relate to the determination of various isotopes in the ^{232}Th Chain. Also shown are the event classifications when there is a scintillator coincidence discussed later in this chapter*

- L-shell electrons drop into the empty K-shell losing either a 5.899 keV or a 5.887 keV X-ray.
- A M-shell electron drops into the K-shell and generates a 6.490 keV X-ray.

Since the PCS detector resolution is not good enough to distinguish these 3 X-rays, the X-rays can be seen as a single X-ray of ~ 5.9 keV. The argon in the PCS then absorbs the γ -ray and produces a photoelectron of energy $E_{\gamma}^{Mn} - (\text{argon K-shell binding energy}) \sim 2.7$ keV. This photoelectron ionizes the gas and deposits its full energy in the PCS gas. The argon atom then relaxes by dropping an electron with a lower binding energy into the core hole. The energy released can be converted into an X-ray or an Auger electron. The emitted X-ray or Auger electron have an energy given by the difference in the argon K and L (~ 2.9) and K and M (~ 3.0) shell binding energies. If a Auger electron is emitted, the full energy of the electron is deposited. However, if a 3 keV X-ray is emitted the X-ray energy is slightly below the argon K-shell absorption edge where the mean free path for secondary absorption is long. Consequently, these X-rays can escape the gas and remain undetected. Therefore, in the PCS there are two peaks visible due to exposure to the ^{55}Fe source, one peak corresponding to the full ^{55}Mn X-ray and a second peak in the X-ray spectrum corresponds to full deposition energy peak minus the energy of argon K-shell electron ($E \sim 5.9 - 3.0 \sim 2.9$).

Figure 6.3 : ^{55}Fe spectrum of a blank cartridge showing the 6 keV X-ray and the argon double escape peak at 3 keV

^{55}Fe Tests with a Blank Cartridge

A PCS cartridge was constructed with no source electroplated on the anode wire. The PCS loaded with this source was placed adjacent to a collimated ^{55}Fe source attached to a caliper, so that its position could be varied with respect to the longitudinal axis of the anode wire. Shown in Figure 6.3 is the ^{55}Fe peaks for the ^{55}Fe source placed adjacent to the position that the electroplated source would be. Here both the 5.9 keV X-ray and 3 keV argon escape peaks are clearly visible. Fitting the 5.9 keV peak to a simple Gaussian suggests a resolution of 17%. This should be compared to the theoretical best resolution of 13% [91] for P10. It should also be noted that the spectrum reveals few events with a pulse height above and below the ^{55}Fe peak, suggesting that all the events observed by the PCS are due to the ^{55}Fe source and that there is little background due to external sources.

Figure 6.4 : ^{55}Fe peak channel, peak rate and Gross rate for the 'PCA' cartridge. The hatched area shows where the source is expected to be located on the wire

To measure the uniformity of the gain along the wire we have varied the position of the ^{55}Fe source adjacent to the PCS and recorded the pulse height of the ^{55}Fe peak at a number of positions along the wire. The peak channel number of the 6 keV X-ray did not change. Therefore, the wire gain is constant along the wire in the blank source within a few per cent.

^{55}Fe Tests with the 'PCA' Source

To determine the quality of the 'PCA' source as compared to the blank cartridge we have conducted similar ^{55}Fe source tests. The first test was to vary the position of the ^{55}Fe source along the 'PCA' cartridge. We measured the ^{55}Fe peak position, the ^{55}Fe peak rate and the total rate (LLD triggered) for the spectrum as a function of position along the wire. The results are shown in Figure 6.4. There was a small loss of gain at the position of the deposition, as shown by the change in the amplitude of the ^{55}Fe peak. This loss of gain is not enough to affect the efficiency of the counter for the electrons. As seen in Figure 6.4, neither the peak rate nor the total rate showed any change as a function of the ^{55}Fe source position along the wire. This

Figure 6.5 : *The variation in the multiplicative gain as a function of wire radius. The formula of Beingessner et al [100] has been used to calculate the gain*

implies that even though there is some loss in the gain, it does not reduce the number of events seen in the PCS.

This change in gain near the site of the electroplated source has been a problem with other sources. This occurs because the electroplating causes a thickening of the wire at the site of the source causing a variation of the gain. This is visible in all sources because a small variation in wire diameter leads to a large variation in the gain (see Figure 6.5).

6.2.3 PCS Pulse Height Tests

LLD Triggered Coincidence Pulse Height Spectrum

Figure 6.6 shows the main characteristics of the counter response to the ^{228}Th source (LLD triggered). This data is taken at 46 psia of P10 gas at 2300 volts and at room temperature. The bump in the spectrum at high amplitude is due to alpha decays in the ^{228}Th chain overloading the pre-amp. In the present context we are mainly interested in the low amplitude pulses from the beta particles. It is only important to note that there is a clear separation in the tail from the

Figure 6.6 : *The pulse height spectrum for source PCA showing the superposition of the response due to the betas and α -particles*

betas and rise from the α -particles, allowing us to set a discriminator to select only α -particles. In the beta part of the spectrum there is a short initial plateau followed by a rise to a broad peak at the beginning of the spectrum. Then, there is a long tail followed by a rise at high pulse heights. These characteristics are explained as follows:

- The beta particles from the wire have a minimum loss for those that go normal to the wire and exit the counter at the center. This means there is a minimum pulse height. This is what causes the rise at the low end of the pulse height spectrum. The solid angle is a maximum for these particles and that is why the spectrum rises to a maximum just above this rise.
- As the electron emission angle moves away from the normal to the wire, the track of the beta in the gas becomes longer and the amplitude of the pulses from the counter

Figure 6.7 : *The pulse height spectrum for source PCA for β - α delayed coincidence events*

increases. The long slow tail reflects the way in which the solid angle changes with particle emission angle.

The LLD·ULD(delayed) Coincidence Pulse Height Spectrum

The 64% ^{212}Bi branch can be selected by triggering on the low amplitude pulses and opening a 350ns delayed 1 μs gate for high amplitude pulses. The pulse height spectrum is shown in Figure 6.7 for these pulses. The amplifier used to feed the pulse height analyzer has a 2 μs time constant. Therefore, it cannot separate the beta particle from the α -particle but produces the spectrum of the sum of the two pulses.

Figure 6.8 : *Energy deposited by 2 MeV (solid) and 1 MeV (dashed) betas in 1 atmosphere P10 gas for the PCS cartridge geometry*

6.2.4 PCS tested with a Scintillator

Beta particles emitted from the PCS exit the counter through the gas of the PCS and the thin 0.7 ± 0.1 mm polycarbonate wall. They will lose very little energy in the gas (see Figure 6.8) and through the thin-walled polycarbonate cylinder. Thus, most of the energy of the beta is deposited in the medium directly outside the counter, which when the PCS is deployed in SNO will be the active volume of SNO.

Therefore, one way of quantifying the response of the PCS in SNO is to surround the PCS with a scintillator optically coupled to a PMT. A coincidence between the scintillator and the PCS requires that a beta or γ -ray is emitted from the ^{228}Th source and is detected in the scintillator and at the same time some energy is deposited in the PCS. Since the α -particles cannot get through the polycarbonate wall of the counter, they will produce no coincidences.

Figure 6.9 : *The pulse height spectrum for source PCA for β - α delayed coincidence events in coincidence with the scintillator*

Also, the efficiency of the thin-walled scintillator is low for γ -rays, so that we do not have a high rate from them. In this way the role of the scintillator is to simulate the SNO PMT assembly in response to the PCS. We have examined the pulse height spectrum produced by the betas and alphas in the PCS both with and without a coincidence with the scintillator.

LLD-ULD(delayed)-Scintillator Coincidence Pulse Height Spectrum

The pulse height spectrum for the delayed coincidence events (as described in the previous section) in coincidence with a scintillator is shown in Figure 6.9. The ratio of the rates measured from event classification corresponding to Figure 6.9 and Figure 6.7 determines the efficiency of the scintillator detecting a ^{212}Bi beta. This parameter is important in extracting the activity of the source as will be explained later. A separate Monte Carlo was written to predict

Figure 6.10 : *The pulse height spectrum for source PCA for PCS events in coincidence with the scintillator*

the scintillator efficiency to the ^{212}Bi branch. The Monte Carlo calculates the energy lost by the ^{212}Bi beta spectrum upon traversing the PCS gas and polycarbonate wall and determines whether the energy deposited is above a certain threshold energy ⁴. The Monte Carlo predicts an efficiency of 50% whereas the experimentally determined efficiency is 60%.

The LLD-Scintillator Coincidence Pulse Height Spectrum

The pulse height spectrum for the PCS in coincidence with the scintillator is shown in Figure 6.10. In this case the beta particles mainly come from the ^{212}Bi and ^{208}Tl decays although there are some from the ^{212}Pb decay. Other coincidences come from α -particles that go to

⁴This is not strictly correct since the full response of the scintillator convolved with the quantum efficiency of the PMT the scintillator is coupled to should be included in the Monte Carlo. However, the efficiency is not very sensitive to reasonable range of threshold energies

excited states of daughter nuclei, that either decay by electron capture or γ -ray emission with enough energy to trigger the scintillator. The bump at the higher amplitudes is due to α -particles from the $^{212}\text{Po} \rightarrow ^{208}\text{Pb}$. The peak at the low amplitudes is the pulse height spectrum due to the beta particles in the proportional counter. The low energy part of the spectrum is mostly produced by beta particles from the $^{212}\text{Pb} \rightarrow ^{212}\text{Bi}$, $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ and the $^{208}\text{Tl} \rightarrow ^{208}\text{Pb}$ decay. Most of the $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ decay electrons will have an α -particle in coincidence with them and be included in the alpha peak.

However, there will be a contribution to the beta spectrum from those beta particles whose associated α -particles are absorbed in the wire. A separate Monte Carlo has been written to calculate the fraction of α -particles that survive the wire. This was done by simulating a point alpha source on the periphery of a stainless steel wire.⁵ The program selects an alpha range for a particular alpha energy from a Gaussian distribution with a mean given by the mean ion depth and a width given by the longitudinal straggling parameter⁶ described in [101]. Then a random direction (θ and ϕ) and radius given by the range is generated, simulating the isotropic emission of α -particles from a source on the wire. Next, the program checks whether the simulated alpha is in the wire or not. If it is in the wire, this corresponds to an event where the alpha is absorbed. Consequently, the ratio of the number of events that are absorbed in the wire divided by the number of events generated gives a quantitative measure of the effect of the wire. The fraction of the α -particles that survive the anode wire was calculated in this way to be 77% for the 8.8 MeV α -particles of the $^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ decay. This parameter is important in extracting the activity from the rates of the various event classifications as will be described in Section 6.2.5.

⁵304 Type is the rating of the stainless steel wire assumed in the calculations (74-69.5% Fe, 18-20% Cr and 8-10.5% Ni)

⁶The range is assumed to be the weighted average of the elemental mixture corresponding to 304 rating stainless steel. The longitudinal straggling parameter is assumed to be that of Fe.

Figure 6.11 : *The pulse height spectrum for the ^{212}Bi beta*

Extracting the Beta Spectrum

The shape of the alpha spectrum in Figure 6.10 is identical with that from Figure 6.7 spectrum since they both come from the same source. Therefore, we have removed the alpha spectrum from Figure 6.10 by normalizing the Figure 6.7 spectrum to the upper part of the spectrum Figure 6.10 and subtracting it. The resulting spectrum is shown in Figure 6.11. The shape can be directly compared to Figure 6.2. The shape can be explained by simulating the pulse height distribution for ^{212}Bi beta events for ^{212}Bi on the wire. The simulation includes the Landau distribution ⁷ for the energy loss in the gas and a Gaussian resolution function to take into account the gain straggling in the PCS. The Gaussian width of the resolution function is the

⁷The Landau distribution was implemented in the simulation using the stand-alone program FLION [98] obtained with permission from the CPC library

Event Type	Experimental Rate	Fitted Rate
R_{ULD}	619.0 ± 3.7	621.5
$R_{LLD \cdot \overline{ULD}}$	328.0 ± 2.0	326.6
$R_{LLD \cdot ULD(\text{delayed})}$	30.4 ± 0.9	30.5
$R_{LLD \cdot \text{Scintillator}}$	97.7 ± 2.9	97.7
$R_{\text{Scintillator} \cdot ULD(\text{delayed})}$	18.8 ± 0.5	18.7
$R_{\text{Scintillator} \cdot ULD(\text{delayed}) \cdot LLD}$	$17.7 \pm 1\%$	-

Table 6.2 : *The experimental values for the rates of various event classifications. $R_{LLD \cdot \overline{ULD}}$ refers to the beta rate, the rate when a LLD triggers without a ULD trigger in the same event. Also shown are the fitted rates corresponding to the equations that are fit in the χ^2 fit described in Section 6.2.5. Note that $R_{\text{Scintillator} \cdot ULD(\text{delayed}) \cdot LLD}$ is not used in the fit.*

width of the ^{55}Fe peak when a ^{55}Fe source is placed on the periphery of the PCA source. The resolution of the peak is considerably worse (22-26%) than the ^{55}Fe peak for the blank cartridge (17%) described in Section 6.2.2. The Monte Carlo beta spectrum was fit to the experimental data where the only free parameter is the horizontal scale (see Figure 6.12). A χ^2 value of 1.2 is obtained where the difference from unity is attributed to multiple scattering and other effects that are not taken into account in the Monte Carlo.

6.2.5 Fitting for the ^{228}Th Activity

The Rates for Various Event Classifications

Each event classification with and without a scintillator coincidence is sensitive to the activity of the ^{228}Th source electroplated on the anode. In this way these equations must be consistent with each other and afford a certain degree of redundancy. This redundancy can be used not only to extract the activity of the ^{228}Th source but also to determine to what precision this activity is known. Therefore, we have made a set of measurements of these rates and then calculated them from the known properties of the counters and the decay schemes. The rates (in Hz) for various event classifications are given in Table 6.2 for source ‘PCA’.

Figure 6.12 : *The Monte Carlo and experimental pulse height spectrum for the ^{212}Bi beta. Experimental data same as as Figure 6.11*

The Rate Equations

Each experimental rate in Table 6.2 can be associated with a specific equation with various experimental parameters, including the activity of the ^{228}Th source. These rate equations are discussed next.

Alpha Rate

$$R_{ULD} = \underbrace{R_{Th}}_1 \underbrace{\sum_{i=1}^{N_\alpha}}_2 \cdot \underbrace{Eff_{\alpha(i)}}_3 \cdot \underbrace{BR(i)}_4$$

- 1) This is the ^{228}Th source activity
- 2) i refers to each alpha (5 α -particles) in the ^{228}Th chain
- 3) This is the Monte Carlo calculated alpha efficiency for the i 'th alpha of surviving the anode wire
- 4) This is the branching ratio for the i 'th alpha.

Beta Rate

$$R_{LLD\overline{ULD}} = R_{Th} \left(\sum_{i=1}^{N_\alpha} \cdot \underbrace{BRE(i)}_1 \cdot \underbrace{Eff_{\beta(i)}}_2 \cdot \underbrace{(1 - Eff_{\alpha(i)})}_3 \right) + \underbrace{\sum_{i=1}^{N_\beta}}_4 \cdot \underbrace{(1 - F_{wall})}_5$$

- 1) This is the branching ratio for the i 'th alpha for an alpha transition to the first excited state releasing an electron.
- 2) This is the beta efficiency for detecting a beta in the PCS for the i 'th beta
- 3) This is the fraction of the i 'th alpha that is absorbed in the wire
- 4) This symbolizes the sum over all the betas in the ^{228}Th chain
- 5) This is the fraction of ^{228}Th that exists on the wire.

Beta-Alpha Delayed Coincidence

$$R_{(LLD\overline{ULD})\cdot ULD(delayed)} = R_{Th} \cdot \underbrace{BR(Bi)}_1 \cdot \underbrace{Eff_{\beta(Bi)}}_2 \cdot \underbrace{Eff_{\alpha(Po)}}_3 \cdot \underbrace{exp^{-0.693 \cdot T_{del}/T_{1/2}}}_4$$

- 1) This is the 0.64 branching ratio of ^{212}Bi to ^{212}Po

- 2) This is the beta efficiency for detecting a ^{212}Bi beta in the PCS
- 3) This is the Monte Carlo calculated alpha efficiency for the ^{212}Po alpha to survive the anode wire
- 4) This is the fraction of $^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ events that have an alpha within a time window that defines the gate for selecting the alpha. T_{del} is a parameter determined only by fitting in a multi-parameter χ^2 fit explained in the next section. This is because the variation in the rise time of the betas causes a jitter in this time window. $T_{1/2}$ is the half-life of the ^{212}Po state.

Equation Used to Determine Scintillator Efficiency

$$R_{(LLD \cdot \overline{ULD}) \cdot ULD(\text{delayed}) \cdot \text{Scintillator}} = R_{Th} \cdot BR(Bi) \cdot Eff_{\beta(Bi)} \cdot Eff_{\alpha(Po)} \cdot \exp^{-0.693 \cdot T_{del}/T_{1/2}} \cdot \underbrace{Eff_{Scint(Bi)}}_1$$

- 1) This is the efficiency of detecting in the scintillator the $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ beta

Beta-Scintillator Coincidence rate

$$R_{LLD \cdot \text{Scintillator}} = R_{Th} \cdot \underbrace{BR(Tl)}_1 \cdot \underbrace{Eff_{Scint(Tl)}}_2 \cdot \underbrace{Eff_{\beta(Tl)}}_3 + R_{Th} \cdot BR(Bi) \cdot Eff_{Scint(Bi)} \left[\underbrace{Eff_{\alpha(Bi)}}_4 + \underbrace{(1 - Eff_{\alpha(Bi)}) Eff_{\beta(Bi)}}_5 \right]$$

- 1) This is the 0.36 branching ratio of ^{212}Bi to ^{208}Tl
- 2) This is the beta efficiency for detecting a ^{208}Tl beta in the scintillator
- 3) This is the efficiency of detecting the ^{208}Tl beta in the PCS
- 4) This is the Monte Carlo calculated fraction of the ^{212}Po α -particles that survive the wire

- 5) This is the number of $^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ events where the alpha is absorbed in the wire, but the beta is detected in the PCS

Scintillator-Alpha Delayed Coincidence Rate

$$R_{Scint \cdot ULD(delayed)} = R_{Th} \cdot BR(Bi) \cdot Eff_{\alpha(Po)} \cdot \exp^{-0.693 \cdot T_{del}/T_{1/2}} \cdot Eff_{scint(Bi)}$$

Scintillator-Alpha Delayed · Beta Coincidence

$$R_{Scint \cdot ULD(delayed) \cdot (LLD \cdot \overline{ULD})} = R_{Th} \cdot BR(Bi) \cdot Eff_{\alpha(Po)} \cdot \underbrace{\exp^{-0.693 \cdot T_{del'}/T_{1/2}}}_1 \cdot Eff_{scint(Bi)} \cdot Eff_{\beta(Bi)}$$

- 1) This is the fraction of $^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ events that have an alpha within a time window that defines the gate for selecting the alpha. $T_{del'}$ is a parameter determined only by fitting in a multi-parameter χ^2 fit explained in the next section. This is because the variation in the rise time of the betas causes a jitter in this time window. $T_{1/2}$ is the half-life of the ^{212}Po state. Note that $T_{del'}$ is slightly different from T_{del} in that it takes into account a difference in the electronic logic in setting up of this coincidence.

Extracting the Activity

The various equations (see Table 6.2) can be fit with a multi-parameter χ^2 fit using MINUIT [102] to extract the activity. The 4 free parameters allowed to float in the fit are:

- $R_{228Th} = ^{228}\text{Th}$ activity electroplated on the PCS anode
- $Eff_{scint(Tl)}$ = The efficiency for observing a ^{208}Tl beta in the scintillator. Note that as mentioned earlier the equivalent efficiency for ^{212}Bi beta is not a free parameter because it is measured.

- T_{del} = The time delay used in the electronic logic to select the delayed α -particle from the $^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$ transition
- $T_{del'}$ = Time delay similar to T_{del} except that it takes into account a small difference in setting up the electronic logic.

The activity extracted from the fit is $\text{Act}_{fit} = 191.5 \pm 0.8$ bq with a χ^2 of 0.96 for experimental and fitted rates). The problem with the fit is that the 3 other parameters besides the activity are almost independently used in 3 of the equations. This means that the parameters can be adjusted independently from each other to reduce the χ^2 .

Monte Carlo was used to predict the fraction of α -particles that survive the wire for each alpha. However, there is almost certainly a build up material on the wire due to the electroplating and the continued operation of the source. It is impossible to estimate this quantity until the cartridge is dissected, so that this is an unknown in the fit. Since all of the α -particle wire survival probabilities calculated are similar (with the exception of the ^{212}Po α -particle), one can multiply all the Monte Carlo calculated values for the alpha survival efficiencies by a common free parameter. This free parameter will account for the effect of the build up of material on the wire not included in the Monte Carlo. The problem is that this free parameter dominates the first 2 equations which contribute to the χ^2 . Therefore, including this free parameter in the fit allows the fit to decrease the χ^2 to zero for the first 2 equations. For this reason the extracted activity must be seen as a combination of the effect of the determination of the activity and that of the thickness of material on the wire. We have other measures of the wire thickness as discussed in previous sections (see Section 6.2.2), in that if there was a significant build up of material at the source, then a ^{55}Fe scan along the wire would detect that. We have measured with the 'PCA' source a 15% reduction of the gain at the center which corresponds to $<1\mu\text{m}$ increase in the build-up on the wire. Using the wire Monte Carlo, we predict that a increase of several micron reduces the alpha efficiency by only a few percent. This is a worst case sce-

nario because this assumes the build-up of material is the wire itself. Therefore, a conservative estimate is that we underestimate the actual ^{228}Th decay rate by 3%.

The ^{228}Th decay rate was also measured using a Ge counter by measuring the intensity of the 238 keV γ -ray from the decay of ^{212}Pb . We compare the intensity of the γ -ray with the PCS as the source with that from a known amount of ^{228}Th used as the source. The absolute Th decay rate by this method is 207 Bq. This has an error of about 10%. This is to be compared with the number from the above table of 191 Bq. The numbers agree within the errors.

6.3 PCS can be triggered or tagged so that its contribution can be identified with respect to the rest of the triggers

The PCS can be run in a tagged mode, such that when a beta or α -particle exceeds the discriminator threshold of the PCS, a logic pulse is sent to one of the inputs of a FEC. If the decay observed in the PCS is due to a ^{212}Bi , or ^{208}Tl beta, the Čerenkov radiation may trigger the SNO NHIT100 trigger, and the event is written out. This will allow the NHIT spectrum to be determined from the trigger threshold to high NHIT. The PCS can also be run in a mode where SNO is triggered whenever a pulse is seen in the proportional counter. This will allow us to determine the full NHIT spectrum. In both modes we determine the NHIT spectrum independent of the photo-disintegration neutron that may follow the initial $\beta - \gamma$ cascade. For this method to be successful we must have a high beta trigger efficiency. In other words we must be certain that whenever a beta decay occurs on the anode wire, it is seen in the PCS.

The beta trigger efficiency can be measured by comparing the Scint·ULD(del) spectrum to the Scint·LLD·ULD(del) spectrum. This is because if we observe a coincidence between the scintillator signal and that from a delayed α -particle, we can be certain that there should be a beta particle in the proportional counter. Therefore, by measuring the rate for this signal and the

rate for a beta particle in coincidence gives us the beta particle efficiency for the beta particles from the $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ decay. This efficiency has been found to be 94% for the counter PCA.

It is important to point out that this measurement is independent of any conditions like pulse height selection or efficiency of either the α -particles or the scintillator. All that is required is that when there is a coincidence between the scintillator and a delayed large amplitude pulse in the proportional counter, we know there was a beta particle produced. Comparing the ratio then tells us whether there actually was a beta detected in the PCS.

This measurement has another significance. If all the Bi were on the cathode of the counter, the beta efficiency would only be 50%. Therefore, a high beta efficiency confirms that the thorium has stayed on the wire. Such that our 96% efficiency shows that less than 8% of the thorium has migrated to the cathode. (Our fit to the data in Table 1 finds a number consistent with zero.) This limit is not very stringent. If the beta particles were on the wall of the counter, their pulse height amplitude would be very broad and have no minimum. This is shown in Figure 6.13 for a Monte Carlo calculation of 40% beta events originating on the wall. Therefore, since the spectrum of the beta particles in Figure 6.12 show a distinct minimum, it is a further evidence that the thorium electroplated on the wire is staying on the wire. This information is supported by post-mortem tests done on other electroplated sources described in Chapter 5 (see Section 5.6.4).

6.3.1 Summary

This discussion started by stating one of the main design criteria of the PCS. The PCS is essentially self-calibrating and the activity can be determined with high precision. We have shown from the previous discussion that we have been able to determine the ^{228}Th activity to $\sim 3\%$ precision. We have also shown that:

- By doing ^{55}Fe tests on the blank cartridge that the source independent background in the cartridge is < 1 Hz.

Figure 6.13 : *The Monte Carlo pulse height spectrum for the ^{212}Bi beta for 40% of betas originating on the wall (dashed line) and all on the wire (solid line)*

- We have measured the gain along the wire of the blank and PCA cartridges and verified that:
 - For the PCA cartridge there is a 15% loss of gain at the position the source is electroplated. This reduces the efficiency for α -particles to survive the anode wire by at most a few percent.
 - ^{55}Fe tests with the blank cartridge verify that the cartridge design is satisfactory in the sense that the resolution is as predicted theoretically and the gain along the wire is constant.
- The pulse height spectrum of the beta in the PCS is as predicted by a Monte Carlo. In particular a fit of the Monte Carlo spectrum to the measured spectrum gives a χ^2 of 0.96.

- The activity of the 'PCA' cartridge was determined to be $191 \pm 3\%$ Bq by a χ^2 fit of the rate equations.

We have also shown that by comparing the ratio of the rates of two event classification the ^{212}Bi beta efficiency in the PCS can be determined. For the 'PCA' source we have measured this efficiency to be 94%, demonstrating that only a small fraction of beta events that will not trigger/tag SNO.

6.4 PCS position must be well determined in SNO

An important design criteria of the PCS is that the source position must be well defined. The uncertainty in knowing the position consists of three sources. First there is the uncertainty in knowing where the source is on the anode wire with respect to the cartridge. This error is expected to be 0.2-0.3 cm. The second uncertainty is the position of the cartridge inside the polycarbonate component. This uncertainty is very small (0.1 cm) because the ridge on the long insert touches the polycarbonate component so that the position is well defined. The dominant uncertainty is the uncertainty associated with the manipulator expected to be ~ 2 -10 cm. Therefore, the error in knowing the position of the PCS when it is deployed is ~ 2 -10 cm. The reconstruction resolution of the PCS is calculated to be ~ 18 cm. Thus, the position of the PCS will be less than the SNO detector resolution.

6.5 PCS must closely approximate a ^{228}Th point source

6.5.1 The PCS Design

A proof in principle that the PCS will not distort the Čerenkov spectrum of the ^{228}Th source requires a full Monte Carlo. However, it is useful to review what aspects of the PCS design satisfies this criterion qualitatively. First, the polycarbonate cylinder has two 13° cones on either side of the cartridge. This is to increase the solid angle for events emitted from the

position where the ^{228}Th is electroplated. The rest of the PCS assembly is pushed in the shadow of the cone, so the fraction of beta events that do not intercept the end caps is 96%. The second reason why the PCS closely approximates a ^{228}Th point source is that the polycarbonate cylinder wall has been made as thin as possible, 0.7 ± 0.1 mm. This ensures that the beta upon traversing the polycarbonate cylinder wall loses little energy, so that the Čerenkov spectrum is minimally distorted. These two reasons combined are the main design considerations to ensure that the PCS geometry will not significantly distort the Čerenkov spectrum.

6.5.2 The Implementation of the PCS Geometry into SNOMAN

A more quantitative test to determine the distortion produced by the PCS geometry to a ^{228}Th point source can be determined by Monte Carlo. This section deals with the implementation of the PCS geometry into SNOMAN, the main SNO Monte Carlo and analysis code.

SNOMAN Geometry Code

While maintaining fast execution time, SNOMAN must correctly simulate the interaction of various particles throughout the entire SNO geometry. To achieve this, the complete SNO geometry has been built up out of *detector elements*, which are described by independent sets of subroutines. The purpose of the code is to handle requests (such as where the particle is, where it is going, how far to the next detector element boundary) by the main geometry processor when a particle is being tracked through a detector element. In addition, each detector element knows only which detector elements border it. To simplify the implementation of the code, each detector element is composed of *primitives* which define the series of geometrical shapes that the detector element is composed of. For example, the active component of the PCS is one detector element. It is modelled by writing code to indicate that the detector element is composed of various primitives, such as two cones and a cylinder. Also, each detector element has a unique identification number that tells the central processor which geometry code to call.

Figure 6.14 : *The PCS source geometry as implemented in SNOMAN. Each point represents an intersection of a neutrino propagation path of a detector element*

At execution time, the code will read from specific data banks:

- The identification number of the detector element
- The exact relation of each primitive which make up a detector element
- The position of the detector element
- The media out of which the detector elements is composed.

This simple way of coding the SNO geometry has the advantage of decreasing the execution time. However, it has the disadvantage that several subroutines must be written for every detector element that make up the SNO detector. See Figure 6.14 for a picture of the PCS geometry as implemented in SNOMAN.

The PCS Geometry in SNOMAN

The PCS geometry is composed of 8 different detector elements and 24 different primitives.

Various compromises have been made to simplify the geometry. First, the brass feedthroughs have been avoided in the geometry since if betas travel toward the feedthroughs they will most certainly be absorbed in the end caps. Second, the stainless steel assembly has been modified, such that the stainless steel cone where the PCS joins with the weight assembly does not need to be simulated. In its place a cylinder of the same media, diameter and weight has been

SNOMAN Region	Description	Number of primitives
ICALI.PCS.LMV	Polycarbonate Component (PCC)	6
ICALI.PCS.GAS	P10 gas	3
ICALI.PCS.CMV	Short and Long Delrin Inserts	4
ICALI.PCS.CCC	Stainless Steel Cap Clamp	1
ICALI.PCS.SMV	Stainless Steel Outer Volume	6
ICALI.PCS.SIV	Stainless Steel Inner Volume	2
ICALI.PCS.WIRE	PCS Anode Wire	1
ICALI.PCS.SOURCE	PCS Source	1
ICALI.PCS.CON*	Protection Cone	1

Table 6.3 : *List of PCS geometry detector elements and number of primitives out of which each detector element is composed. * refers to polypropylene cone added to PCS when deploying H₂O to prevent it from catching on obstructions in the guide tube.*

implemented. Table 6.3 lists the detector elements that make-up the PCS geometry:

User Control

SNOMAN calls a separate program (known as a ‘command file’) for instructions on what is to be simulated or which data to be analyzed. The command file is how the user interacts with SNOMAN and instructs SNOMAN what tasks need to be done and under what conditions. The command file also tells SNOMAN which geometry and media data banks need to be included at execution time. Using the command file the user can change the media, turn on various detector elements and change the position the PCS is to be simulated at. The user can deploy the PCS both in the H₂O and in the D₂O, although the current code is not efficient, since rather than the same code handling deployment in H₂O and in the D₂O, two sets of code have been written to handle deployment in each region.

Simulation of the Polycarbonate Component

The crucial detector element in the PCS geometry is the PCC. Satisfaction of the original design criteria that the PCS acts essentially as a point source of ²²⁸Th means that we must not only prove that the distortion of the PCS geometry to the Čerenkov spectrum is minimal, but

we must also prove that the distortion is not very sensitive to optical parameters assumed in the Monte Carlo. For this reason, it is necessary to ensure that the PCC optical properties are properly implemented, but that variation of optical parameters does not adversely affect the beta Čerenkov spectrum. SNOMAN uses optical parameters, such as the refractive index and absorption coefficient to simulate the propagation of the Čerenkov photons. For the inclusion of the PCC, the optical properties of a particular type of acrylic currently not used has been modified and called in SNOMAN as a media for the PCC. The absorption coefficient as a function of wavelength and mean refractive index has been changed to match polycarbonate. The original data in the form of the transmission coefficient as a function of wavelength has come from a General Electric internal document [103]. This data has been converted to an absorption coefficient and fit to a polynomial for inclusion in SNOMAN.

In order to assess the effect of optics of the polycarbonate on the Čerenkov spectra, we have done a set of Monte Carlo runs where various optical parameters such as the index of refraction and absorption coefficient are changed. All of these Monte Carlo runs show little dependence on the polycarbonate optics. The most convincing comparison is Figure 6.15 which shows the NHIT distribution for the PCS ^{208}Tl spectra and for the PCS with the media changed to acrylic with the absorption coefficient increased by two orders of magnitude. This effectively turns off this medium as an optical media and essentially increases the attenuation to make it opaque. Also, shown in the figure is the same simulation but with the polycarbonate absorption increased by 20%. It should be noted that the effect of the uncertainty of the polycarbonate optics on the Čerenkov spectra produced by the PCS seems to be small. Furthermore, it is important to determine effect the optics of the PCS has on the isotropy of the ^{208}Tl source. Figure 6.16 shows the θ_{ij} ⁸ distribution for the PCS, for acrylic where the attenuation has been increased by two orders of magnitude and for the PCS with the polycarbonate absorption

⁸The θ_{ij} parameter measures the angle between all hit PMTs, this was described in Chapter 3

Figure 6.15 : *The Monte Carlo NHIT spectrum for PCS with polycarbonate (error bars), PCS with 20% increase in absorption coefficient (solid error band) and for acrylic with attenuation increased by a factor of 100 (open error band)*

coefficient increased by 20%. The variation due to the PCS optics in distorting the isotropy also seems to be small.

Comparison of PCS to ^{228}Th Point Source: Center of D_2O

NHIT Spectra As stated earlier, one of the most important design criteria is that the PCS geometry should not significantly distort the beta Čerenkov spectrum. In other words, the PCS geometry should match as closely a point source of ^{228}Th . Figure 6.17 shows a comparison of the PCS geometry to a point source for a one million event simulation done with SNOMAN version 4.0192. Here it is seen that there is some loss of light due to the PCS geometry which

Figure 6.16 : *The Monte Carlo θ_{ij} spectrum for PCS with polycarbonate (error bars), PCS with 20% increase in absorption coefficient (solid error band) and for acrylic with attenuation increased by a factor of 100 (open error band)*

shifts the spectrum towards lower energies. The relevant region for the neutrino analysis is $\text{NHIT} > 30$, therefore it is more instructive to look at this $\text{NHIT} > 30$ region. Figure 6.18 shows the same Monte Carlo data set as Figure 6.17 for $\text{NHIT} > 30$. One way of quantifying the difference between the PCS and the point source spectrum is to compare the ratio of the number of events in each $\text{NHIT} > 30$ spectra. For the Monte Carlo calculation shown in Figure 6.18 the ratio is 0.79 for $\text{NHIT} > 30$. This means that if we use uncorrected PCS NHIT spectrum and naively count the observed background where $\text{NHIT} > 30$ in SNO, we will overestimate the activity by 30%. If we do the same calculation for $\text{NHIT} > 25$, we overestimate the true ^{208}Tl activity by 15%.

Figure 6.17 : Comparison of NHIT spectrum of PCS (error boxes) and a ^{228}Th point source (error bars) at the center of SNO. One million events were simulated with SNO-MAN 4.0192

The θ_{ij} Distribution As mentioned in Chapter 4, SNO uses an isotropy parameter θ_{ij} to separate low energy background of the ^{232}Th chain from the ^{238}U chain. In order to calibrate the *In-Situ* method it is necessary to compare the Monte Carlo generated distribution to that of a calibration source. The θ_{ij} distribution of the PCS and for a ^{208}Tl point source for one million events is shown in Figure 6.19.

One can subtract the two spectra in Figure 6.19, where the difference is a measure of the similarity of the two distributions, but also of the separation of the peaks in the distributions. For example, if the two θ_{ij} distributions would be identical and the means of the two peaks coincide, the difference distribution would be zero for all bins. In contrast, if the two distributions were entirely separated, the difference in the two distributions would be the two distributions

Figure 6.18 : Comparison of NHIT spectrum of PCS (error band) and a ^{228}Th point source (error boxes) at the center of SNO for $\text{NHIT} > 30$. One million events were simulated with SNOMAN 4.0192

themselves. It is the difference in the two distributions up to the point where the distributions intersect that is a measure of the separation of the two distributions.

This is best illustrated in Figure 6.20 where the θ_{ij} distributions are plotted for ^{208}Tl and for ^{214}Bi for the PCS deployed at the center of SNO. As mentioned in Chapter 4, it is the difference in these distributions that allows the thorium and uranium background to be statistically separated. Also shown in Figure 6.20 is the absolute value of the difference between the ^{214}Bi and ^{208}Tl distributions. Two peaks (referred to as ‘difference peaks’) are visible. The first peak corresponds to an excess of ‘Bi-like’ events and the second peak corresponds to an excess of ‘Th-like’ events. Therefore, the ratio of the ‘difference peaks’ to the number of events in the distribution itself (up to the intersection of the θ_{ij} distributions (see line in Figure 6.20)) is a

Figure 6.19 : Comparison of θ_{ij} spectrum of PCS and a ^{208}Tl point source (shaded) at the center of SNO for $\text{NHIT} > 25$. One million events were simulated with SNOMAN 4.0192. Also shown is the absolute value of the difference in the two distributions

measure of the separation of the two peaks. In the case of Figure 4.9, the comparison of the θ_{ij} distributions for a point source, the ratio of the first difference peak to the number of events in the ^{214}Bi distribution (up to the point where the θ_{ij} distributions intersect) is 32%. The second difference peak ratio to the number of events in the ^{208}Tl distribution for θ_{ij} exceeding the point where the two θ_{ij} distributions intersect is 42%. If the ^{214}Bi and ^{208}Tl distributions were entirely separated, the ratio would be 100%.

Furthermore, in Figure 6.19 the ratio of the area of the difference peak to the ^{208}Tl θ_{ij} point

source distribution is 4% for $\theta_{ij} < 1.33$ and 8% for $\theta_{ij} > 1.33$. Therefore, there is a significant difference between the PCS and ^{208}Tl point distributions for $\theta_{ij} > 1.33$, whereas for $\theta_{ij} < 1.33$ the difference between the two distributions is less pronounced. This is important because a shift in the θ_{ij} distribution for the PCS toward lower θ_{ij} means that the PCS will look more ‘Bi-like’ than ‘Th-like’. If the uncorrected θ_{ij} is used to fit the SNO data, the amount of Th will be overestimated⁹. This is because the excess of events for the ^{214}Bi point source as compared to the ^{214}Bi PCS source means that if the PCS θ_{ij} distribution is fit to background data to minimize the χ^2 , the number of ^{208}Tl events need to be increased at the expense of the number of ^{214}Bi events. This will be discussed in more detail in the next section. Figure 6.20 shows the θ_{ij} distributions for the PCS and for ^{214}Bi . In this case the ratio of the two peaks to the distributions themselves is 32% and 42% respectively. This should be directly compared to ratios 36% and 44% in Figure 4.9, the higher ratio indicates better separation.

Using PCS to extract the fraction of ^{208}Tl and ^{214}Bi in a data set The *in-situ* method has been developed to extract the fraction of ^{208}Tl and ^{214}Bi in a SNO background data set (see Chapter 4). The technique consists of generating ^{208}Tl and ^{214}Bi PDF’s in θ_{ij} and fitting this to the observed low energy background in SNO. We have done this for Monte Carlo data in order to determine how the distortion of the θ_{ij} distribution due to the PCS geometry, effects the efficiency for classifying background events. First, PDFs in θ_{ij} were produced at the center of SNO, for both ^{208}Tl and ^{214}Bi for the PCS geometry and for a point source. Next, a mixed ^{208}Tl and ^{214}Bi point source geometry sample was produced. Care was taken to ensure that each Monte Carlo data set has a different starting seed in the random number sequence. In principle, there exists an amplitude ($\mathcal{A}_{Tl}$ and $\mathcal{A}_{Bi}$) whose product with each PDF corresponds to the actual number of events in the data set since the background data set is only composed of the two (^{208}Tl and ^{214}Bi) components. To find this amplitude for each PDF, a χ^2 fit is performed

⁹A discussion of correcting the data using Monte Carlo is postponed until Chapter 7

Figure 6.20 : The θ_{ij} distributions for both the PCS ^{208}Tl (shaded) and ^{214}Bi for a point source at the center of the SNO active volume. Also shown is the absolute value of the difference of the two distributions.

using CERNlib's MINUIT [102] fitting the sum of the scaled PDF's to the mixed data set. The scales correspond to the amplitudes and are the free parameters in the fit. The χ^2 function to be minimized is written as:

$$\chi^2 = \frac{\mathcal{A}_{Tl} * PDF_{Tl}(\theta_{ij}) + \mathcal{A}_{Bi} * PDF_{Bi}(\theta_{ij}) - DATA(\theta_{ij})}{\delta^2}$$

Where $DATA(\theta_{ij})$ is the θ_{ij} distribution for the background mixed data set and δ is the sum of the uncertainties of the two PDF's and the background data set added in quadrature.

When the ratio of ^{214}Bi to ^{208}Tl in the mixed data set and the PDF's for the point source are used, the χ^2 fit extracts the fit parameters as $\mathcal{A}_{Tl}=6945\pm245$ and $\mathcal{A}_{Bi}=4310\pm226$. Thus, the ratio of ^{214}Bi to ^{208}Tl is $0.62\pm10\%$. This is in agreement with the known mixture of ^{208}Tl and ^{214}Bi in the background data set of 0.65. If the same fit is performed with the PCS PDF's, the distortion in the θ_{ij} PDF causes the ratio of ^{214}Bi to ^{208}Tl to be $0.34\pm10\%$. This

is an underestimation of 52%. The underestimation of the number of ^{214}Bi events is caused by the depreciation of events for $\theta_{ij} > 1.33$ for the PCS source as discussed in the previous section (See Figure 6.21 for the PDF's for ^{214}Bi and ^{208}Tl for a point source and the PCS). However, instead of fitting the full range of the θ_{ij} distribution, we can ignore the area of the distribution where the PCS does not agree with the point source and fit only in the region $\theta_{ij} < 1.33$. When this is done, the fit becomes considerably better: the χ^2 improves and the extracted number of ^{208}Tl and ^{214}Bi events approaches those of the known population of ^{208}Tl and ^{214}Bi in the data set. This is shown in Figure 6.22 for a fit of the Monte Carlo PCS PDFs to a mixed data set. Also shown in the figure is the full θ_{ij} range fit greatly overestimating the population of ^{208}Tl in the mixed data set. It should be mentioned that there really is only one free parameter (either $\mathcal{A}_{Tl}$ or $\mathcal{A}_{Bi}$) since the other amplitude is fixed by the total number of events in the background data set. However, fitting for two parameters allows the amplitudes to vary independently, which is necessary if the fit extracts the efficiency for the number of events differently for different isotopes. For example, as discussed earlier, the restricted θ_{ij} range fit extracts the ^{214}Bi population in the mixed data set close to the actual value, whereas $\mathcal{A}_{Tl}$ is always underestimated. Therefore, if a one parameter ($\mathcal{A}_1$) fit is done corresponding to either $\mathcal{A}_{Tl}$ or $\mathcal{A}_{Bi}$, the fit restricts the other amplitude ($\mathcal{A}_2$) to the number of events minus $\mathcal{A}_1$. This causes $\mathcal{A}_1$ to be wrong and with a $\chi^2 \gg 1$, because $\mathcal{A}_2$ has no room to vary. For these reasons the two parameter fit is used in this technique.

To get a sense of the sensitivity of the *in-situ* technique with PCS PDF's for extracting ^{208}Tl and ^{214}Bi in practice, it is useful to use a more realistic data set for the contamination of ^{208}Tl and ^{214}Bi in the D_2O . The recommended weighted average of the amount of ^{214}Bi and ^{212}Tl using the *in-situ* and *ex-situ* methods are given in Table 6.4. A mixed ^{214}Bi and ^{208}Tl point source data set was constructed in the same proportion of Th and U as the recently measured concentrations in the D_2O . Next a χ^2 fit is performed in the full region of θ_{ij} and in the region $\theta_{ij} < 1.33$. The result of the fit distribution is shown in Figure 6.23. The actual ratio

Figure 6.21 : The Monte Carlo calculated PDF's for a point source (solid) and the PCS (dotted) for a) ^{214}Bi and b) ^{208}Tl isotopes. Note the differences in the ^{214}Bi PDF's in the region $\theta_{ij} > 1.33$.

Figure 6.22 : Comparison of fits of PCS PDFs to a mixed ^{208}Tl and Bi data set for different regions of θ_{ij} . Note that if the full range of θ_{ij} is used in the fit the amount of ^{208}Tl is over-estimated. Note that the PCS and point source Monte Carlos that make up the mixed data set were both generated at the center of the D_2O .

of ^{208}Tl to ^{214}Bi for the mixed data set is 11.5% and the fit extracts a ratio of 8.5% when the fit is restricted to the region $\theta_{ij} < 1.33$ with a $\chi^2 \sim 0.93$. When the concentration of ^{232}Th in the background data is varied in increments of 10% above and below the recommended value listed in Table 6.4, the fit is sensitive to variation and suggests changes in ^{208}Tl concentration ranging from 10-20%. The fits also show that the underestimation of the ^{208}Tl concentration by the PCS PDF is not very sensitive to the ratio of Th to U. This is important since it gives us confidence in the method.

Isotope	Concentration
$^{232}\text{Th} (\rightarrow ^{208}\text{Tl})$	$1.63 \pm 0.58 \times 10^{-15} \text{ g Th / g D}_2\text{O}$
$^{238}\text{U} (\rightarrow ^{214}\text{Bi})$	$17.8^{+3.2}_{-4.3} \times 10^{-15} \text{ g U / g D}_2\text{O}$

Table 6.4 : Measured concentrations of Th and U giving rise to ^{208}Tl and ^{214}Bi contamination as determined using the in-situ and ex-situ techniques [69]

Figure 6.23 : Comparison of fits of PCS PDFs to a mixed ^{208}Tl and ^{214}Bi data set for the region $\theta_{ij} < 1.33$. The mixed data set corresponds to the same ratio of ^{208}Tl to ^{214}Bi events as the measured concentrations [69] in the D_2O . Note that the PCS and point source Monte Carlos that make up the mixed data set were both generated at the center of the D_2O .

Comparison of PCS to ^{228}Th Point Source: H_2O

The present plan as will be discussed in the next chapter is for the PCS to be deployed in the H_2O . This is important for the reasons outlined in Chapter 4. The NHIT spectra for 200k events for the PCS deployed at a radius of 653 cm is shown in Figure 6.24.

One of the main uses for the PCS when deployed in the H_2O is to set a limit on the leakage of background events in the fiducial volume. This will be done by deploying the PCS throughout the H_2O and observing the number of events that reconstruct inside the fiducial volume. Figure 6.25 shows the radius of events originating from the PCS reconstructing inside the D_2O for a point source and the PCS.

Figure 6.24 : *Comparison of NHIT spectrum of PCS (shaded) and α ^{208}Tl point source at $R=653$ cm for $\text{NHIT}>25$. 200k events were simulated with SNOMAN 4.0192*

6.5.3 The Actual Proof of Principle: Engineering Run

In Oct 2000 the PCS was deployed at the center of the D_2O for an engineering run. The source on the anode of the PCS was a very low activity, <1 Bq, ^{228}Th source. NIM level logic was set-up so that whenever a beta or α -particle was observed in the PCS, SNO was triggered using *EXT4* of the external trigger inputs (see Section 3.2.6). See Figure 6.26 for the *EXT4* triggered NHIT spectra.

In the ^{228}Th chain there are also five α -particles that do not produce Čerenkov light. Therefore, the low energy shoulder in the *EXT4* triggered NHIT spectrum is due to random external triggers. The second feature in the data is the SNO response to the ^{228}Th $\beta-\gamma$ Čerenkov spectra that appears at the high NHIT part of the spectrum. Also shown in Figure 6.26 is the scaled

Figure 6.25 : Number of events reconstructing in the D_2O for PCS deployed at $R=653$ cm (shaded) and ^{208}Tl point source. 200k events were simulated with SNOMAN 4.0192

PCS SNOMAN calculation $NHIT > 17$ (dashed) that includes the full PCS geometry and the convolution of the $\beta - \gamma$ cascades from ^{212}Bi and ^{208}Tl . The dotted line in the figure is for a ^{228}Th point source where the PCS geometry is turned off in SNOMAN. It is seen that the PCS SNOMAN simulation is in agreement with the *EXT4* triggered PCS data.

Using SNO Data to Calibrate PCS Source

We have also used the $NHIT > 16$ spectrum in the PCS SNO data to calibrate the PCS source deployed. This part of the spectrum is in the tails of the lightless trigger spectrum produced from α -particle triggers and should correspond to the Čerenkov spectrum due to the ^{228}Th source. More precisely the sum of the 64% ^{212}Bi and 36% ^{208}Tl beta gamma's coming from ^{228}Th . Here it is assumed that the ^{228}Th source was at equilibrium. The number of PCS *EXT4* triggered events with $NHIT > 16$ for run 13800 was 2618.

A higher statistics PCS Monte Carlo calculation of 500k ^{214}Bi events and 281k ^{208}Tl events summed the $NHIT$ distribution for both Monte Carlo runs and scaled it to produce the same

Figure 6.26 : A comparison of Run 13800 (solid) with the Monte Carlo of the source (dashed) and a ^{228}Th point source (dotted). The simulations were performed with SNO-MAN 4.0180.

number of 2618 events. The amplitude needed to do this is 0.0203. This means that to produce 2618 ^{228}Th chain events 15.85k events would have been needed over the time duration of the run. The run duration is 3.92 hours so that the calibrated activity using the high NHIT region of the raw NHIT spectrum is 1.12 Bq ^{228}Th . This should be compared to the ^{228}Th source rate of 1.8 Bq measured by using the ^{212}Bi delayed coincidence in the PCS. The discrepancy in the two determinations of the ^{228}Th activity can be understood when the cartridge was dissected. Post-mortem tests showed that there was considerable activity on the walls of the PCS cartridge. This meant that the beta track length will not have a true minimum as is the case when the ^{228}Th is on the anode (see Figure 6.13). In this case some of the events will not trigger SNO and produce the discrepancy.

6.6 Summary

In the previous chapter we aimed to convince the reader that the PCS will not compromise the physics in SNO (point 5 above). The purpose of this chapter was to adress all the other design criteria to convince the reader that the PCS has met them. The main points are:

- **[1] PCS ^{228}Th source activity is a well known constant**
 - The ^{55}Fe tests on the blank cartridge show that the source independent background in the cartridge is <1 Hz.
 - We have measured the gain along the wire of the blank and PCA cartridges and verified that:
 - * For the PCA cartridge there is a 15% loss of gain at the position the source is electroplated. This reduces the efficiency for α -particles to survive the anode wire by at most a few percent.
 - * ^{55}Fe tests with the blank cartridge verify that the cartridge design is satisfactory in the sense that the resolution is as predicted theoretically and the gain along the wire is constant.
 - The spectrum pulse height spectrum of the beta in the PCS is as predicted by a Monte Carlo. In particular, a fit of the Monte Carlo spectrum to the measured spectrum gives a χ^2 of 0.96.
 - The activity of one of the source cartridges was determined to be $191 \pm 3\%$ Bq by a χ^2 fit of the rate equations to the measured rates.
- **[2] PCS can be triggered or tagged so that its contribution can be identified with respect to the rest of the triggers**
 - The beta trigger efficiency can be measured by comparing the Scintillator·ULD(del) spectrum to the Scintillator·LLD·ULD(del) spectrum. With

the cartridge 'PCA' the beta trigger efficiency was found to be $>96\%$.

- **[3] PCS position must be well determined in SNO**
 - A conservative estimate for knowing the error in the position of the PCS when it is deployed is ~ 1 cm.
- **[4] PCS must closely approximate a ^{228}Th point source**
 - The SNOMAN Monte Carlo suggests that the difference between the PCS and a ^{208}Tl point source is small. This is verified by the spectra obtained in an engineering run.

Chapter 7

Run Plan and Analysis Flow of PCS Source

7.1 Introduction

The previous chapters convince the reader that the PCS has met the criteria established in Chapter 4. The ‘proof in principle’ is that data taken during the engineering run corresponds closely to what is expected from the Monte Carlo of the PCS and a ^{228}Th point source. The purpose of this chapter is to review the run plan and procedures for deployment in the light water and briefly describe the analysis.

7.2 Deployment of PCS in H_2O

A scientific review of the PCS was performed in April 2002 with the recommendation that the PCS should be deployed in the light water “at the earliest convenience”. Consequently, a run plan and a set of procedures were written to ensure a successful deployment.

The current plan is to deploy the PCS with a 50 Bq ^{228}Th source on the anode of the proportional counter. The PCS pressurized with 51 psia P10 has maintained a constant pressure over the course of several weeks. This allows the PCS to be filled with counting gas at Carleton University rather than at SNO greatly decreasing the risk of contamination underground.

The PCS is to be deployed through a guide tube, which is a vertical tube which connects to

Figure 7.1 : NIM level logic showing the tags and triggers

the PSUP and allows access to the light water volume. The particular guide tube that the PCS is proposed to be deployed through corresponds to the coordinates $(x,y)=(-586,208)$, where the Z axis is the vertical axis. The PCS is to be run for 4 hours ($\sim 200k$ Tl-208 decays) per point, for 11 different points in the H₂O active volume. The proposed electronic logic is shown in Figure 7.1.

7.3 Tags and Triggers:

We would like to send the following triggers and tags to the SNO electronics:

- **LLD Tag:** This TAG is simply given by any event in the PCS which fires the Low Level Discriminator (LLD). There are 2 beta decays and five α -particle particle decays in the decay chain. Of these, only the betas from ^{212}Bi - ^{212}Po and ^{208}Tl - ^{208}Pb will give a signal in SNO. Since they sum to 1, only 1 in seven of the decays can activate the SNO trigger. Since the PCS beta efficiency is high, we would expect most of the SNO triggers from the source to be accompanied by a this tag.

- $LLD \cdot \overline{ULD}$ Tag: This Tag will remove the α -particle signals from the tag and will only fire for the ^{212}Bi , ^{208}Tl and ^{212}Pb beta particles. The ^{212}Bi decay for prompt α -particle particles will be removed, but those Bi beta particles, for which the α -particle is absorbed in the wire or for which the α -particle is delayed beyond the α -particle veto will still be in this signal. The ^{212}Pb betas will also be in this tag.
- ULD Tag : This tag will select all those ^{212}Bi decays which have ULD firing.
- $LLD \cdot \overline{ULD}$ Trigger : This trigger will send the beta particle triggers to the SNO electronics. It will select the ^{212}Bi and ^{208}Tl beta spectra down to low NHIT. ^{212}Pb will also fire this trigger but will have no SNO coincidences with them since the maximum beta endpoint energy for ^{212}Pb is below the Čerenkov threshold.
- $LLD \cdot \overline{ULD} \cdot ULD(\text{del})$ Trigger: This trigger lets us select those $LLD \cdot \overline{ULD}$ events which are followed by a delayed α -particle. This trigger will be given a fixed additional delay, so that it will appear in the next readout cycle of the SNO electronics. This is because the delay of the α -particle is so long that it would normally be missed in the Čerenkov event seen by the SNO electronics.

7.3.1 Significance of Procedures

As the PCS was developed, it became clear that one can not depend solely on the execution of procedures as a safe-guard against a condition leading to thorium contamination. In fact, it is the goal of the author of the procedure to write a procedure that is clear, concise and easy to follow and when a failure condition is tested, a backup diagnosis is always performed. As has been mentioned, one of the main criteria for deployment is to ensure that the PCS will not risk contamination of SNO. If the PCS fails, it must not only fail safe, but procedures must also be in place to ensure that the correct response is executed, given the specific failure condition. It is with this “spirit” that the PCS deployment procedures have been written. The procedures

aim to be simple, transparent and to depend on human intervention as little as possible.

Most of the steps in the procedures are to diagnose problems with the mechanical integrity of the PCS and the electronics. At various stages in the procedures the operator is prompted for a YES/NO answer regarding a diagnosis of a condition of the PCS. These questions are to determine whether there is a loss of pressure or a failure with the associated electronics or preamplifier at various parts of the procedure. If a NO answer is given, the instructions that follow describe what can be done to determine what the problem is. In all of the cases of failure on surface, the procedure must be stopped and repeated until the result is YES. For the procedures underground the instructions for NO answer are more restrictive. In almost all cases, the instructions call for the stopping of the procedure along with the expulsion of the PCS equipment from underground. The appropriate responses to each specific failure condition is given in the procedures in the form of a response number.

However, as mentioned earlier, the goal of writing the procedures is to be as independent as possible of human intervention (i.e. procedure). Thus, at no stage during the procedure are critical diagnoses performed that if improperly done could lead to a direct exposure of SNO to PCS gas. For example, rather than requiring the operator to close a valve when the PCS is disconnected from the PCS gas system, an interlocking valve is instituted which disallows the valve from being opened when the PCS is detached from the gas system. Another way to remain independent of human intervention is to use electronic means to diagnose problems. This is described in the next section.

7.3.2 Diagnoses of Failure Conditions by Alarm

Failure modes are also diagnosed by the activation of the alarms on the MANIM module (see Section 5.4.5). Light Emitting Diodes (LED's) on the MANIM module describe which of the 3 alarms (Pressure, Rate, HV Trip) have caused the alarm to be activated. In Figure 7.2, each failure scenario can be looked up and the corresponding condition number is given. The

operator must then apply the instructions given in the description of the condition and execute the appropriate response number. Each response number corresponds to a particular procedure that must be carried out if the failure condition occurs. This quantifies and restricts what activities are carried out. Each response procedure is organized according to where the incident has occurred. Figure 7.2 shows the various failure conditions from the most serious on the top left, calling for immediate expulsion of the PCS from underground to the bottom right where the appropriate reaction does not require the PCS run to be stopped.

7.4 Procedure and Schedule for Proposed H₂O

The procedure for deployment consists of a 12-day plan requiring the operator to conduct tests at Carleton University as well as at SNO on surface and underground. The PCS procedures are to be performed for 2 complete separate PCS source assemblies. The motivation for having 2 PCS sources prepared for deployment is that if something goes wrong with one PCS, a new leached PCS can be deployed. The conditions of this replacement is described in detail in the set of PCS procedures [104]. A brief sketch of the procedures and the order they are executed are given in Tables 7.1 and 7.2.

7.5 Analysis of H₂O Run

The main objective of the PCS as described in Chapter 3 is to characterize the SNO response to thorium and in particular, to ^{208}Tl . This will be done by deploying the PCS at 11 different points within the H₂O. The PCS spectra at each point are then volume and activity weighted before they are summed to produce a final spectrum corresponding to the expected response of SNO to a uniformly distributed source of ^{208}Tl ¹. The spectra corresponding to a known activity will then be fit to the SNO low energy background data to extract the activity present

¹This process is described in more detail in the next section.

Figure 7.2 : Diagram showing the combination of alarms corresponding to various failure conditions (C) and the appropriate responses (R). Note that the thicker lined box corresponds to the case where a specific alarm is on

DAY 1: Carleton University

- Implement "Gas Evacuation and Fill Procedure"
 - This procedure consists of filling and evacuating the PCS 3 times until a final fill with 50 psia P10.
- Implement "PCS Pre-Deployment at Carleton Procedure"
 - Electronic tests are done with a standard test cable
 - Overnight pressure test is implemented to verify that the pressure remains constant
 - PCS is placed in an ice water tank (*cold test*) to confirm that the cold temperature does not adversely affect the PCS pressure seal.

DAY 2: Carleton University

- "PCS Pre-Deployment at Carleton Procedure" continued
 - Results of the overnight pressure and cold tests.
- Implement "PCS Leaching Procedure"
 - This procedure involves placing the PCS sources in ultrapure water for approximately 3 days.

DAY 3-5: Carleton University

- Both PCS sources and the weight assembly are leached in a Carleton clean room.

Day 5: Transport to Site: Wednesday

- The leaching is completed and is sent to chemists at SNO for analysis of the Th-228 content using the HTiO technique
- Implement "PCS Transport Procedure"

Day 6: Transport Underground: Thursday AM or PM Shift

- Implement "PCS Pre-Deployment Underground Procedure"
 - Various underground electronic tests are performed
 - Overnight pressure test and continuous monitoring of the pressure to verify that there has been no damage to the PCS due to transport underground.

Day 7: Underground: Friday AM or PM Shift

- Result of PCS overnight pressure tests
- Various tests for electronic problems
- A PCS dummy source (Complete PCS assembly with no ^{228}Th source present)
 - Execute "PCS Assembly Procedure" for dummy source
 - Execute "PCS Deployment Procedure" for dummy source.
- Monitor pressure of the PCS to be deployed during the weekend

Table 7.1 : *A summary of the deployment plan for PCS in the H_2O . For a detailed description see report [104].*

Day 8: Underground: Monday AM and PM Shift

- Leaching samples counted for 3 days, if OK continue with procedure
- Implement "PCS Assembly Procedure"
- Implement "PCS Deployment Procedure"
 - PCS electronics interfaced with SNO
 - PCS deployment via guide tube (-586,208) to Z=0 corresponding to R=620 cm
 - PCS diagnostics
- Run for 4 hours at (-586,208,151) R=640 cm
- Retract source in glove-box at end of shift

Day 9: Underground Tuesday AM/PM Shift

- Run for 1 hour at (-586,208,0) R=620 cm
 - Are the rates at (-586,208,0) consistent with previous day?
- Run for 4 hours at (-586,208,221) R=660 cm
- Run for 4 hours at (-586,208,275) R=680 cm
- Run for 2 hours at (-586,208,321) R=700 cm
- Retract source in glove-box at end of shift

Day 10: Underground Wednesday AM/PM Shift

- Run for 1 hour at (-586,208,0) R=620 cm
 - Are the rates at (-586,208,0) consistent with previous day?
- Run for 2 hours at (-586,208,321) R=700 cm
- Run for 4 hours at (-586,208,362) R=720 cm
- Run for 4 hours at (-586,208,401) R=740 cm
- Retract source into glove-box at end of shift

Day 11: Underground Thursday AM/PM Shift

- Run for 1 hour at (-586,208,0) R=620 cm
 - Are the rates at (-586,208,0) consistent with previous measurement?
- Run for 4 hours at (-586,208,436) R=760 cm
- Run for 4 hours at (-586,208,503) R=800 cm
- Run for 2 hours at (-586,208,534) R=820 cm
- Retract source in glove-box at the end of shift

Day 12: Underground Friday AM/PM Shift

- Run for 1 hour at (-586,208,0) R=620 cm
 - Are the rates at (-586,208,0) consistent with previous measurement?
- Run for 4 hours at (-586,208,534) R=820 cm
- Retract source in glove-box at the end of shift

Table 7.2 : PCS Run Plan and schedule for deployment in H_2 . This is a continuation of Table 7.1

in SNO. However, it is expected that there is more activity near the acrylic vessel and PSUP than throughout the light water volume. Therefore, the PCS spectra obtained at various places close to the acrylic vessel or PSUP will be weighted more heavily than just warranted by the volume weighting in order to test the hypothesis of whether there are higher activities near the extrema of the light water volume. The appropriately weighted spectra will then be fit to the SNO low energy background data to extract the activity. Unfortunately, the PCS has not been deployed yet, and thus, this analysis is not included in this thesis. Nevertheless, the following section will outline in more detail one way how the analysis may proceed.

7.5.1 Extracting the ^{208}Tl Shape

The key ingredient in the analysis of PCS data is the knowledge of the activity of the ^{228}Th electroplated at the center of the PCS cartridge. It is expected that we know the PCS ^{228}Th activity to $\sim 3\%$ by extracting the activity using the χ^2 fit described in the previous chapter. Next, since the activity of the PCS source is known, the response in SNO to the activity can be measured. This gives us the shape of the distribution. By knowing the activity of the PCS, we can then associate the activity to an observed amplitude.

The normalized ^{208}Tl SNO response or probability density function (PDF) produced by the PCS is labelled as $S_{PCS}^{DATA}(R_i, v)$. Here, R_i corresponds to the radius at which the PCS is deployed and v is any variable of interest that could correspond to NHIT, energy as extracted using the RSP processor (see chapter 3), θ_{ij} , or R^3 . In the following discussion the PDF will be generated for the NHIT variable. In fact, the PCS geometry produces some distortion to the Čerenkov spectra and hence the distributions of the various variables of interest. Therefore, the *true* SNO response to a point source of ^{208}Tl is labelled $S_{True}^{DATA}(R_i, v)$. It is the goal of the analysis to extract the true distribution of a ^{208}Tl point source throughout the detector volume. Thus, for a perfect containerless source it would be the case that $S_{PCS}^{DATA}(R_i, v) = S_{True}^{DATA}(R_i, v)$. However, in the case of the PCS this is not true. There is a variation in the

shape and also in the amplitude. Let us represent the binned contents of the PDF's S (above) of variable v by a column vector of dimension n , corresponding to the number of bins in the distribution. That is:

$$\mathcal{M}(R_i, v) * S_{PCS}^{DATA}(R_i, v) = S_{True}^{DATA}(R_i, v) \quad (7.1)$$

Where $\mathcal{M}(R_i, v)$ is the $n \times n$ matrix containing all the information (essentially the operator) necessary to convert the PCS data PDF into the PDF for the true SNO response for variable v at any point throughout the SNO active volume. To solve the above equation, it is necessary to determine the matrix $\mathcal{M}$. If the Monte Carlo is trusted and the matrix is diagonal, this matrix can be determined by Monte Carlo. In this case the jj 'th elements of the $\mathcal{M}$ matrix are:

$$\mathcal{M}(R_i, v)_{jj} = \frac{S_{True}^{MC}(R_i, v)_j}{S_{PCS}^{MC}(R_i, v)_j} \quad (7.2)$$

Where $S_{True}^{MC}(R_i, v)_j$ and $S_{PCS}^{MC}(R_i, v)_j$ are the Monte Carlo determined SNO response to a point source of ^{208}Tl and the PCS source. This assumes that the PCS does not produce any smearing of the true ^{208}Tl point source distribution, but only limits the number of events in each bin of variable v . Once we know the matrix $\mathcal{M}$, we can correct the observed distribution of the PCS for variable v by multiplying by the matrix $\mathcal{M}$ determined from Monte Carlo. An example of the diagonal elements of the $\mathcal{M}$ matrix for a PCS run at $R=621$ and $R=698$ is shown in Figure 7.3 where the diagonal components of the $\mathcal{M}$ matrix correspond to the bin contents. It is clear that to determine these components to high NHIT, it is necessary to do simulations with much more statistics. However, knowing the shape $S_{True}^{MC}(R_i, v)$ will not allow us to extract the activity of a ^{208}Tl point source. We must also know the relative normalization factors between the PCS and SNO true point source data. In this way we know what activity is associated with an observed amplitude in SNO. This is discussed in the next section.

To have confidence in the method above to extract the matrix $\mathcal{M}$ we must believe the Monte Carlo and must know that the PCS and the ^{208}Tl point source distributions for variable v are

Figure 7.3 : *The diagonal components of the M matrix determined by Monte Carlo for 500k events at $R=621\text{cm}$ (error bars) and at $R=698\text{cm}$ (error band).*

not very different. In this section the comparison is shown for the Monte Carlo determined distributions for the PCS and the ^{208}Tl point source for the case where the variable v corresponds to the NHIT distribution. To test the analysis several Monte Carlo runs were performed of the PCS deployed down the guide tube that corresponds to the coordinates $(-586, 208)$. The PCS is then deployed with different Z coordinates corresponding to different radii(R) from the center of SNO. PCS Monte Carlos were run at positions $R=621, 639, 650, 698, 786, 812, 833$ corresponding to a 2 hour run with a 200 Bq ^{228}Th source ² for both the ^{208}Tl point source and the full PCS geometry. In Figure 7.4 the NHIT PDFs for the PCS and the ^{208}Tl point source are shown for a 2 hour run with a 200 Bq ^{228}Th source at $R=621$ cm, 20 cm away from the acrylic vessel. Once the PCS is moved closer to the PSUP, the acceptance of SNO decreases because the reflectors shield the PMTs from seeing a large component of the light water. See Figure 7.5 for the Monte Carlo generated PCS and ^{208}Tl point source distributions for deployment near the PSUP. For this reason, one observes that there is a lot less Čerenkov light in the NHIT spectra.

7.5.2 Calibrating the Amplitude of the ^{208}Tl Spectra

The preceding discussion concerned only with the shape of the distribution of the PCS as compared to a ^{208}Tl point source. However, as mentioned, the shape alone does not allow us to extract the activity. We must have a relative normalization factor between the spectrum observed in SNO from the PCS ($N_{PCS}^{DATA}(R_i, v)$) and the true response of SNO to a point source ($N_{True}^{DATA}(R_i, v)$) whose ratio $T_{DATA} = \frac{N_{PCS}^{DATA}(R_i, v)}{N_{True}^{DATA}(R_i, v)}$ must remain constant regardless of run duration. Since the PCS intercepts some light and essentially shifts the spectrum to lower NHIT, one expects that the number of events for the same activity source above a higher NHIT threshold is less for the PCS than for a ^{208}Tl point source, such that $T < 1$. The variable T

²In the proposed PCS run it is planned to use a 50 Bq ^{228}Th cartridge, however it is desirable to use a higher 200 Bq cartridge such as 'PCA' discussed in Chapter 5

Figure 7.4 : The PDF constructed from Monte Carlo generated NHIT distribution for a 2 hour run with a 200 Bq ^{228}Th source in the PCS (solid line) and the ^{208}Tl point source (dashed line) at $R=621\text{cm}$.

Figure 7.5 : The PDF constructed from Monte Carlo generated NHIT distribution above NHIT 20 for a 2 hour run with a 200 Bq ^{228}Th source in the PCS (solid line) and the ^{208}Tl point source (dashed line) at $R=833\text{cm}$.

then allows us to relate the amplitude of a known activity source electroplated on the PCS to the amplitude of the distribution of a point source in SNO. For the PDF's shown in Figure 7.4 and Figure 7.5, the values of T determined by Monte Carlo for $NHIT > 10$ and $NHIT > 20$ are $0.97 \pm 0.1\%$ and $0.89 \pm 3\%$ respectively.

7.5.3 Comparison of the PCS PDF to Uniformly Distributed ^{208}Tl PDF

It is instructive to compare the appropriately weighted PDF distributions obtained by PCS Monte Carlo to a uniformly distributed ^{208}Tl source. First, the Monte Carlo obtained PCS and ^{208}Tl point source NHIT PDF's were volume weighted to account for the difference in volume each point represents. For example, a run at $R=620$ cm will represent a smaller volume than a run at $R=830$ cm. The volume weighting was done by dividing the volume up into shells, so that the edge of each shell is exactly $1/2$ the distance to the next point. Thus, the volume weight for the PDF for point R_i corresponds to the volume shell surrounding this specific point divided by the total volume in the light water. The event weighting for each point was done by dividing the number of events in each run by the events simulated. The event weighting accounts for the variation in efficiency as the PCS is deployed closer to the PSUP. That is, even though the volume increases as R is increased, the detector efficiency decreases (less events are detected due to the shielding of the light water by the reflectors) and thus, the contribution the events near the PSUP make to the final weighted PDF is small ³.

The volume and event weighted NHIT PDF's are shown in Figure 7.6 for the PCS deployed at $R=621, 639, 650, 698, 786, 812, 833$ and corresponding to a 2 hour run with a 200 Bq ^{228}Th . Also shown in Figure 7.6 is the equivalent distribution obtained by volume weighting the NHIT PDFs for a ^{208}Tl point source deployed at the same points.

It is expected that the activity nearer to the PSUP is much higher than the activity in the light

³This assumes that the activity is uniformly distributed throughout the H_2O this is of course not the case since we know that the PSUP and the Acrylic Vessel are significant sources of activity

Figure 7.6 : *The PDF constructed from Monte Carlo generated volume and event weighted NHIT distributions above NHIT 20 for 2 hour runs with a 200 Bq ^{228}Th source in the PCS (error bars) and and the ^{208}Tl point source (error band). The error corresponds to the propagated statistical error for summation of the weighted PDF's for each run.*

Figure 7.7 : *The error bars correspond to the PDF constructed from Monte Carlo generated volume and event weighted NHIT distributions above NHIT 10 for a 2 hour run with a 200 Bq ^{228}Th source in the PCS. Also shown are the uniformly distributed ^{208}Tl source (bottom error band) and the same source weighted 10 times higher near the AV and PSUP (top error band). The error corresponds to the propagated statistical error for summation of the weighted PDF's for each run.*

water. Since the PSUP itself is a large mass leaching a large amount of thorium into the light water. Also, the PMTs themselves are expected to contribute to the low energy background. In addition to the background from the PSUP, the thorium activity near the AV is also known to be higher than the activity in the light water. For these reasons, it is interesting to weight the activities corresponding to an increase in activity near the AV and the PSUP. This is shown in Figure 7.7 and Figure 7.8 where the Monte Carlo runs were weighted to correspond to 1 and 2 orders of magnitude more activity at the PSUP and AV than in the light water itself. One sees that shape of the volume weighted PCS PDF may also be sensitive to assessing differences in the activity throughout the H_2O .

Figure 7.8 : *The error bars correspond to the PDF constructed from Monte Carlo generated volume and event weighted NHIT distributions above NHIT 10 for 2 hour runs with a 200 Bq ^{228}Th source in the PCS. Also shown are the uniformly distributed ^{208}Tl (bottom error band) ^{208}Tl source and the same source weighted 100 times higher near the AV and PSUP (top error band). The error corresponds to the propagated statistical error for summation of the weighted PDF's for each run.*

7.6 Summary

In this chapter we have discussed the proposed plan for deployment of the PCS in the H_2O . The run plan calls for deploying the PCS at 11 different points through the guide tube that corresponds to the coordinates $(-586, 208)$ (the Z axis is parallel with the guide tube). The PCS is then deployed at varying values of Z to correspond to different radii from the center of the SNO active volume. In this way, the response of SNO to the PCS can be tested at various different radii. We have also shown the technique we plan to apply to extract the shape of a ^{208}Tl source in SNO and how to combine the various different runs to compose a volume and event weighted PDF. We have also shown that the PCS shape will also be sensitive to the variation of activity in the H_2O since it is expected that there is an increase in activity near the AV and the PSUP. Finally, we have demonstrated a method for associating the PCS activity to an activity of a ^{208}Tl point source in SNO, by fitting the PCS spectrum corrected by the M matrix to the SNO low energy background data. It should be mentioned that all the examples of the techniques discussed are described assuming that the NHIT variable is the parameter of interest. However, the techniques are general and any parameter, such as R^3 , θ_{ij} , or energy determined by RSP can be used.

Chapter 8

Summary of this Thesis

The main purpose of this thesis is to describe a novel method of calibrating the SNO detector's low energy background. The technique consists of a proportional counter with various isotopes occurring naturally in SNO electroplated on the anode. The Proportional Counter Source, its motivation for construction, design, testing, procedures for deployment and analysis are the focus of this thesis. The 5 main design criteria and how we have met them as stated in Chapter 4,5,6 are:

- [1] **PCS cannot pose a risk to SNO**
 - PCS has been rigidly tested for mechanical strength, material compatibility, radon emanation tests, drop tests etc.
 - PCS has a set of procedures in place to maintain quality control whose main purpose is to prevent cross-contamination.
 - PCS program has several quality assurance requirements. Tests have been conducted where PCS gas has been purposely depressurized through a filter and the filter counted for ^{228}Th activity. No evidence was found for excess ^{228}Th activity. The second important requirement of a PCS source is that the PCS when placed in UPW for 3 days, cannot leach more than 140 ^{228}Th atoms. These requirements have to be met each time a PCS source is deployed.

- A set of safety considerations stated at end of chapter 5.
- **[2] PCS ^{228}Th source activity must be a well known constant**
 - By doing ^{55}Fe tests on the blank cartridge that the source independent background in the cartridge is <1 Hz.
 - We have measured the gain along the wire of the blank and PCA cartridges and verified that:
 - * For the PCA cartridge there is a 15% loss of gain at the position the source is electroplated. This reduces the efficiency for α -particles to survive the anode wire by at most a few percent.
 - * ^{55}Fe tests with the blank cartridge verify that the cartridge design is satisfactory in the sense that the resolution is as predicted theoretically and the gain along the wire is constant.
- **[3] PCS can be triggered or tagged so that its contribution can be identified with respect to the rest of the triggers.**
 - The beta trigger efficiency can be measured by comparing the Scintillator·ULD(delayed) spectrum to the Scintillator·LLD·ULD(delayed) spectrum. With the cartridge 'PCA' the beta trigger efficiency was found to be $>96\%$.
- **[4] PCS position must be well determined in SNO**
 - A conservative estimate for knowing the error in the position of the PCS when it is deployed is ~ 1 cm.
- **[5] PCS must closely approximate a ^{228}Th point source**
 - The SNOMAN Monte Carlo suggests that the difference between the PCS and a ^{208}Tl point source is small. This is verified by the spectra obtained in an engineering run. In addition, the Monte Carlo simulations show that the PCS spectra and

isotropy is not sensitive to uncertainty in polycarbonate optics.

Chapter 7 focusses on the proposed run plan for deploying the PCS in H_2O . The current run plan is to deploy the PCS through a guide tube at 11 points. The complete procedure has been written and is a detailed 12 day plan which guarantees that the technique is safe. The run plan requires that two leached PCS sources to be ready to be deployed in case one of the sources fails. We have also described the technique planed to extract the shape of a ^{208}Tl source in SNO and how to combine the various different runs to compose a volume and event weighted PDF. We have also shown that the PCS shape will also be sensitive to the variation of activity in the H_2O , since it is expected that there is an increase in activity near the AV and the PSUP. Finally, we have demonstrated a method for associating the PCS activity to an activity of a ^{208}Tl point source in SNO, by fitting the PCS spectrum corrected by the $\mathcal{M}$ matrix to the SNO low energy background data. It should be mentioned that all the examples of the techniques discussed were described assuming that the NHIT variable is the parameter of interest. However, the techniques are general and any parameter such as R^3 , θ_{ij} , or energy determined by RSP can be used.

Appendix A

PCS Component Reference

Component	Vendor	Part Number
PM	G.S. Sensors	XPM5
PA- HV in	W. W. Fischer	S103 A023/6.7-S
PA- HV out	W. W. Fischer	SF 102 A002
Hermetic HV Feedthrough	W. W. Fischer	DBEE 102 A002
locking clip	AMP	87615-1
locking clip housing	AMP	87133-7

Table A.1 : *Information on PCS components, vendor and part number*

Appendix B

PCS Schematics

Figure B.2 : Schematic of MANIM module

Figure B.3 : Schematic of PPNIM module

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