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INVESTIGATION OF THE TRIGGERED SOURCE TECHNIQUE FOR THE CALIBRATION OF SNO

by

Ferenc Dalnoki-Veress

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

Ottawa-Carleton Institute for Physics
Department of Physics, Carleton University
Ottawa, Ontario, Canada
January 22, 1996

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INVESTIGATION OF THE TRIGGERED SOURCE TECHNIQUE
FOR THE CALIBRATION OF THE SUDBURY
NEUTRINO OBSERVATORY

submitted by Ferenc Dalnoki-Veress, B.Sc.,

in partial fulfillment of the requirements
for the degree of Master of Science

Thesis Supervisor

Chair, Department of Physics

Carleton University

Date: Jan 29 '96

Abstract

If a clean measurement is to be made of the charged current to neutral current ratio, and charged current spectral distortion, the low energy background in the Sudbury Neutrino Observatory (SNO) must be very well understood. The triggered source technique is a method for calibrating the response of the SNO detector to specific background sources. The technique relies on a proportional counter source (PCS), which acts both as a detector, as well as a source. This report summarizes the results of the first stage of testing the technique, in a cylindrical tank with 2 photomultiplier tubes (PMT's). To determine what events are observed by the PCS and PMT's, two event classification techniques were developed, an electronic method, and a computational method. The computational method has proven to be more advantageous, consequently this technique will be utilized in the future. Theoretical rate equations have been developed to predict the rates of various event types. The results of a 5 free parameter χ^2 fit of the experimentally observed rates to the theoretical rates are discussed in this report. Monte Carlo studies to verify the validity of the extracted free parameters in the χ^2 fit are reported. Various design modifications to the prototype PCS for the next stage of testing the technique are discussed.

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This work is dedicated to my father.

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Chapter 1

The Solar Neutrino Problem

1.1 Introduction

It is believed that the physics of how the sun works is well understood. 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 (ν) flux predicted due to energy production in the sun is not what is expected. A discrepancy with experiment 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[1]. Later, three new experiments came on-line, and reinforced the discrepancy by also observing a deficit in the ν flux. This deficit became known as the solar ν problem (SNP). Rather than artificially adjusting various parameters in the SSM to fit data, a new mechanism was proposed that changed not the astrophysics of how the sun works, but suggested that not all is known about the propagation of electron ν 's (ν_e 's) ² through space and matter. The possibility was raised that upon travelling through the solar interior and space,

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 all solar ν experiments are compared to.

²In this report ν will be used when the flavour is not significant to the context in which the symbol is used. ν_e is used when it is important to emphasize that the particle is an *electron* ν .

ν_e 's change into ν 's of other flavours (such as μ or τ) rendering them undetectable by existing solar ν experiments which are mainly sensitive to ν_e 's. (A brief description of the four existing solar ν experiments and various solutions to the SNP are described in this chapter). For these ν oscillations to occur, it is required for ν 's to have mass. This is a reasonable extension to the Standard Model of particle physics since ν 's are assumed to be massless only as a consequence of terrestrial experiments.

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 may finally be realized, with the construction of the Sudbury Neutrino Observatory (SNO) deep in a mine in Ontario, Canada. SNO 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 (PMT's), that surround the heavy water, and detect the Čerenkov radiation produced by electrons that are emitted as a result of ν interactions. Each ν interaction has a specific signature, that 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 model independent comparison to be made of the solar ν flux of various flavours. Thus, if SNO observes an excess of counts for the NC reaction as compared to the CC reaction, it confirms the oscillation of ν_e to other flavours.

To make the CC and NC measurements, the low energy background in SNO must be very well understood. The low energy background is mainly due to the decay of beta (β) emitters in the ^{232}Th and ^{238}U radioactive decay chains, producing Čerenkov radiation that masquerade as the Čerenkov light produced by a ν interaction. The low energy background which appears as an exponential increase towards lower energies, is known as the background wall. The shape of the background wall determines the low energy limit of ν detection, and thus tells us the fraction of the

ν spectrum that SNO is sensitive to. Understanding the shape of the background wall, will be attained by employing a proportional counter, with various β 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 β 's that are 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 produce Čerenkov radiation. The surrounding SNO PMT's that detect Čerenkov radiation will pick up the signal. The main advantage of the technique, is that the signal due to the isotope can be determined independent of other β -emitters, because by tagging the β in the proportional counter we can neglect other backgrounds. Consequently, by placing various isotopes on the anode of the PCS, the shape and amplitude of the response of the SNO detector to every component of the background wall can be assessed. Now, if the source strength of the PCS is a known quantity, we have an absolute calibration of the activity in the PCS, to the amplitude of the spectra observed by the SNO PMT's. For this reason it is imperative that the activity of the PCS is measured very accurately. This report will summarize the progress in the first stage of the experimental investigation of this technique.

The testing of the proportional counter source is facilitated by using the Čerenkov Cell which is essentially a very small test version of SNO. The Čerenkov Cell is a cylindrical tank filled with light water and lined with a reflecting aluminum layer. On each side of the cylindrical tank is one PMT which will simulate the 9600 PMT's surrounding the SNO active volume. The proportional counter source is mounted in the centre of the tank surrounded by an acrylic cylinder. So when the source decays and produces a β it will travel through the acrylic, and produce Čerenkov radiation which is detected by the two PMT's, just as it would be detected in SNO by the sphere of PMT's surrounding the heavy water. In this way, the conditions and design modifications of the proportional counter source can be determined for the successful deployment of the technique in SNO.

1.2 Solar ν 's

It is believed that stars, like the sun, obtain their energy by nuclear fusion. Alternative sources of energy, such as gravitational, would be expended on a time scale much smaller than is known from observation³. The sun generates its energy by hydrogen burning, fusing 4 protons into an α , two positrons and two ν_e 's.

According to the SSM, the current model of the sun, this reaction can occur through 2 processes, the pp-chain (shown in Figure 1.1) which accounts for 98.5% of the energy produced in the present day sun, and the CNO cycle⁴ accounting for the remaining 1.5 %. In each reaction 26.731 MeV is released, of which on average only

Figure 1.1: The pp-chain

0.572 MeV is carried away by the ν_e 's in each termination⁵. The photons that we

³For example, we can estimate the age of the solar system and hence the minimum age of the sun by dating meteoric rocks.

⁴The CNO cycle (carbon-nitrogen-oxygen) generates energy by a similar chain of nuclear fusion reactions as the pp-chain, however it is aided by ${}^{12}\text{C}$.

⁵Termination is defined as each 4 protons are converted to one α

see, only give us information about the outer edge of the sun, and thus will do little to explain what is happening in the centre of the sun. The ν_e 's however, come to us straight from their place of birth, and are not scattered by the solar interior. Thus the ν flux and differential energy spectrum, gives us information about the nuclear reactions occurring in the sun. The main types of ν producing reactions that are of experimental interest are shown in Table 1.1.

Source	$E_{\nu}^{\max}$ (MeV)	flux ($\text{cm}^{-2}\text{s}^{-1}$)		
		BP(with diffusion)	BP(without)	TCL
1) $^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu$	1.20	4.92E8	4.35E8	3.83E8
2) $^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu$	1.73	4.26E8	3.72E8	3.18E8
3) $^{17}\text{F} \rightarrow ^{17}\text{O} + e^+ + \nu$	1.74	5.39E6	4.67E6	
4) $^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu$	~ 15	5.69E6	5.06E6	4.43E6
5) $^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu$	18.77	1.23E3	1.25E3	
6) $p + p \rightarrow ^2\text{H} + e^+ + \nu$	0.42	6.00E10	6.04E10	6.03E10
7) $^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu$	0.86(90%)	4.89E9	4.61E9	4.34E9
	0.38(10%)			
8) $p + e^- + p \rightarrow ^2\text{H} + \nu$	1.44	1.43E8	1.43E8	1.39E8

Table 1.1: ν fluxes predicted by three SSM's: the Bahcall/Pinsonneault (BP) SSM with and without He diffusion, and Turck-Chièze/Lopez (TCL) SSM's.

The first six reactions of Table 1.1 produce β -decay ν spectra with the endpoints given as $E_{\nu_e}^{\max}$ [2]. The other two reactions produce mono-energetic ν 's with a width characteristic of thermal broadening in the sun.

Several experiments have been performed to detect ν_e 's and thus 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 centre of the sun, the low interaction cross section of ν 's with matter, makes the detection of these particles very difficult. The typical cross section for solar 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 may be minimized. Currently, only four of these experiments are in operation, and may be divided into 2 classes. First,

there are the radiochemical detectors that detect ν 's by extracting and counting the resultant nuclei produced by the ν absorption reactions. These detectors only give information about the flux and the temporal variations in the ν_e flux on a time scale of years. Second, are the real time, direct counting experiments that detect electrons and gammas (γ 's) produced by the initial ν interactions. These detectors do not only give information about the ν flux, but also about the directionality and differential energy spectrum of the ν sources. The direct counting experiments are sensitive to temporal variations from microseconds to years.

1.3 Solar ν Experiments

1.3.1 The ^{37}Cl Experiment

The first experiment to detect ν 's from the sun, was the radio-chemical experiment by Davis *et.al*[3]. The experiment was based 1490 m underground in the Homestake Gold Mine (4900 mwe⁶). The experiment uses as its target for the ν_e absorption reaction, 0.615 kt perchloroethylene (C_2Cl_4) which has 133 tons ^{37}Cl . The experiment utilizes the ν_e 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_e 's (reaction 6 in Table 1.1) and the 0.38 MeV ^7Be line (see Figure 1.2). This experiment has been running continuously⁷ since 1967.

The Cl experiment proceeds in four steps. First, a known amount of carrier gas that is composed of isotopically pure ^{36}Ar or ^{38}Ar is dissolved into the C_2Cl_4 . Then, the C_2Cl_4 active volume is left to stand, exposed for about 3 months to the solar

⁶mwe 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.

⁷Except for a 17 month period in 1985/86 when there were failures in the circulation pumps

Figure 1.2: The predicted spectrum of solar ν 's according to the Bahcall-Pinsonneault SSM.

ν 's. Next, by purging with He gas, and by collecting the Argon in a cryo-trap, the Argon atoms are removed from the active volume, so that more than 95% of the Argon is extracted⁸. The extracted Argon gas is separated from the reactive and noble gases that are present in the mixture, and the purified argon is added to a methane counter gas, and loaded into a small proportional counter. As the ^{37}Ar decays back to ^{37}Cl (half life ($T_{1/2}$) ~ 35 days), a 2.82 keV Auger electron is detected in the proportional counter. Using the fact that the resolution of the proportional counter is $\sim 25\%$, and that the rise time of the Auger electron is very fast⁹, and by employing various geometric cuts, the background is minimized. The proportional counter is monitored for ^{37}Cl decay for about 1 year ($10 T_{1/2}$'s). The latest results, along with the theoretical estimates for the ^{37}Cl experiment are shown in Table 1.2.

⁸The extraction efficiency is determined for each run by comparing the known amount of ^{38}Ar injected as the carrier gas in the active volume to the amount extracted.

⁹The 2.82 keV electron will produce only a few hundred ion pairs because of its short range, consequently the pulse rise time will be very fast

Detector	BP SSM	TCL SSM	Experiments
Kamiokande	1 ± 0.14	0.77 ± 0.19	$(0.51 \pm 0.07 \text{ BP SSM})$
Homestake (Cl)	$8 \pm 1 \text{ SNU}$	$6.4 \pm 1.4 \text{ SNU}$	$2.32 \pm 0.26 \text{ SNU} (0.29 \pm 0.03 \text{ BP SSM})$
SAGE & GALLEX (Ga)	$131.5^{+7}_{-6} \text{ SNU}$	$122.5 \pm 7 \text{ SNU}$	$78 \pm 10 \text{ SNU} (0.59 \pm 0.08 \text{ BP SSM})$

Table 1.2: The SSM predictions of Bahcall and Pinsonneault (BP) and of Turck-Chize and Lopes (TCL), along with the results of the solar ν experiments (1 SNU $\sim 10^{-36}$ captures/s/target atom).

1.3.2 The ^{71}Ga Experiments

Since, 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, 0.42 MeV, and this makes the ν 's very difficult to detect, because of large detector backgrounds. The GALLEX and SAGE Collaborations have utilized the reactions:

which has a Q-value of -0.233 MeV, below the endpoint of the pp ν_e 's.

The GALLEX experiment, situated at Gran Sasso underground laboratory (3300 mwe), uses 30.3 tons of Ga as a solution of GaCl_3 in HCl . Initially, a known amount of non-radioactive Ge ($\sim 1 \text{ mg}$) is added to the solution, so that the extraction efficiency can be determined for each run. After an exposure to solar ν_e 's of about 3 weeks, the ^{71}Ge that is produced is extracted as GeCl_4 . The GALLEX Collaboration claims an overall extraction efficiency of 99% for the Germanium. The GeCl_4 is then chemically converted to the gas germane (GeH_4), a methane like gas, that is used both as the ^{71}Ge radioactive source, and when mixed with Xe as the counting gas in a miniature proportional counter (active volume $\sim 0.5 \text{ cm}^3$, counting efficiency 65.8% [4]). When the ^{71}Ge that is produced, due to the ν_e interactions, decays by electron capture ($T_{1/2} \sim 11.43 \text{ days}$) back to ^{71}Ga , Auger electrons and x-rays deposit energy in the counter, and are detected. The counting time in these ultra low background

proportional counters is about $15 T_{1/2}$'s, so that an accurate assessment can be made of the background. The proportional counter itself is placed in a NaI counter, that acts as an anti-coincidence shield, vetoing any external pulses coincident with signals in the proportional counter. Various cuts are invoked at the analysis stage, so that backgrounds caused by the ^{232}Th and ^{238}U chain are minimized. Pulse shape discrimination is also imposed by demanding fast rise times, similar to the ^{37}Cl experiment.

The second ^{71}Ga experiment is the Russian American Gallium Experiment (SAGE) which is located at the Baksan Neutrino Observatory (4700 mwe). It is very similar to GALLEX in the extraction of the ^{71}Ge except that 60 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 also, since the volume is much smaller, it 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. The SAGE experiment claims an overall extraction efficiency of about 90%. Similar amplitude and rise time cuts are employed at the analysis stage, as is done with the data from the GALLEX experiment. SAGE has been taking data since January 1990, and GALLEX since May 1991. The latest results, along with how these compare with theoretical calculations are shown in Table 1.2.

1.3.3 The Kamiokande Experiment

The Kamiokande¹⁰ experiment is located 1 km below ground, in a mine in the Japanese Alps (2700 mwe). 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 PMT's, providing a 20% photocathode coverage¹¹. The

¹⁰The Kamiokande experiment has gone through several generations of upgrades denoted by K1, KII, and KIII.

¹¹This is to be compared to a 60% photocathode coverage of the SNO, to be described later in this report.

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 PMT's, which detect cosmic ray muons passing through the water, and consequently veto the inner detector, so that these events are ignored. Kamiokande is sensitive to the highly forward elastic scattering (ES) reaction:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

by detecting the Čerenkov radiation produced by the recoiling electrons. The low energy background wall fixes the energy threshold above 7.5 MeV, so that the Kamiokande experiments are only sensitive to ^8B ν 's (see reaction 4 in Table 1.1)¹².

To do energy calibration in Kamiokande, the electrons from stopped muon decays (Michel Spectrum), and the subsequent high energy β 's are detected, and compared with what is expected from Monte Carlo. Timing calibration of the PMT's and electronics is achieved using a nitrogen laser ball, which emits a 337 nm isotropic light pulse for 3 ns. The backgrounds present at Kamiokande are not discussed, since they are similar to the light water backgrounds in SNO, and will be analyzed in Chapter 2 of this report. In the analysis of the data, various cuts have been invoked. Besides the selected fiducial volume, a further directional cut is imposed on the events that reconstruct inside the fiducial volume. In general, the external γ 's that come from the rock are sufficiently collimated, that they enter the detector normal to the wall of the cavity, which is taken into account in the analysis¹³. Because of Kamiokande's directional sensitivity (angular resolution 28° to 20° from 10 to 20 MeV respectively [5]), they were the first to positively prove, that the sun is a source of ν_e 's. The current data, and its comparison to theoretical calculations, is shown in Table 1.2.

¹²Kamiokande is sensitive to hep ν 's (see reaction 5 in Table 1.1) as well, but these have a flux three orders of magnitude less than the ^8B ν 's.

¹³This is also true for the SNO detector to be described later.

1.4 The SNP

A quick glance at Table 1.2 reveals a clear discrepancy of theory with experiment, this is the SNP. In the evolution of solar ν physics the problem has only become more intense, and has challenged the SSM's, and thus our understanding of how the sun works. Historically, the Cl experiment mentioned earlier measured a ν_e flux about 1/3 of that predicted by the SSM's. Later, Kamiokande came on-line, and also measured the ν_e flux to be well below what is expected. At this stage doubt was cast on whether the ^8B flux was calculated correctly in the SSM.

A series of 1000 Monte Carlo calculations [6] were done, where the input parameters to the SSM were randomly sampled from a Gaussian distribution, with the mean given by the 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 1.3 and Figure 1.4 below.) Furthermore, if the ^8B flux in the 1000 SSM's was changed artificially,

Figure 1.3: J.N. Bahcall's 1000 solar models for the chlorine experiment

so that the Kamiokande ^8B ν flux would be the input parameter, then the 1000 SSM's would still not agree with the Cl experiment. Not only were the experiments

Figure 1.4: J.N. Bahcall's 1000 solar models for the Kamiokande experiment

not agreeing with the SSM, but they were not even agreeing with each other. As a consequence of this inconsistency, many believed that one of the experiments was not correct. 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.

In the 1990's the Ga experiments (GALLEX and SAGE) started counting, and an even more extreme anomaly was discovered. Not only were the ^8B ν 's suppressed, the ^7Be ν 's were completely missing¹⁴, 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 [7] express the SNP very clearly. With a few minor assumptions¹⁵ and assuming that the results from all 4 solar ν experiments are correct, they extract the experimentally obtained ^7Be ν

¹⁴The 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.

¹⁵The 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 standard solar models (NSSM's), these flux ratios remain practically constant.

flux ($\Phi_{7\text{Be}}$) and the flux due to the CNO cycle ν 's (Φ_{CNO}). They obtain a ${}^7\text{Be}$ 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 zero (we 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), then the physical $\Phi_{7\text{Be}}$ consistent with all 4 experiments is negative. This is shown in Figure 1.5 where the experimental results are shown for each experiment (with areas defined as the areas allowed at 1σ) in the $\Phi_{\text{B}} - \Phi_{7\text{Be}}$ plane, with the assumption that $\Phi_{\text{CNO}} = 0$. Here it is seen that the allowed areas of

Figure 1.5: The regions allowed in the $\Phi_{\text{B}} - \Phi_{7\text{Be}}$ 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 Lissia, along with the 1σ error bars.

all 4 experiments intersect in the non-physical region, where $\Phi_{7\text{Be}}$ is negative. This inconsistency of theory with experiment, is the SNP at present. There are only four solutions possible which will now be discussed.

1.4.1 Experimental Solutions

The solution proposed is that one or more of the experiments are not correct. Referring to Figure 1.5 it can be seen qualitatively, that if one of the experiments is rejected, the intersecting 1σ regions of the other experiments are still unphysical. If a χ^2 analysis is performed under the constraint $\Phi_{\text{CNO}} \sim 0$ (the best case for reproducing results predicted by the SSM), where $\Phi_{7\text{Be}}$ and Φ_{B} 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 1.6, and Table 1.3, where various combinations of experiments are fit[7]) to the SSM of Degl'Innocenti, Fiorentini, and Lissia (DFL)¹⁶. From Table 1.3 it is seen that the

Experiment Combinations	C.L. of ${}^7\text{Be} \leq 0$	Maximum ${}^7\text{Be}$ flux $10^9 \text{cm}^{-2}\text{s}^{-1}$ height		
		90% C.L.	95% C.L.	98% C.L.
(a) Cl+Ga+Ka	87%	0.2	0.6	1.1
(b) Cl+Ga	45%	1.7	2.1	2.7
(c) Cl+Ka	88%	0.1	0.9	1.6
(d) Ga+Ka	59%	1.1	1.6	2.1

Table 1.3: The second column shows at which confidence level (C.L.) four different combinations of present experimental data imply a negative ${}^7\text{Be}$ flux, i.e. nonstandard ν 's (see text). The combinations are the signals of (a) Homestake (Cl) + GALLEX and SAGE combined (Ga) + Kamiokande (Ka), (b) Cl + Ga, (c) Cl + Ka and (d) Ga + Ka. The other columns show the maximum beryllium flux allowed by the same combinations of data at the 90%, 95% and 98% C.L.

Kamiokande and Cl experiments cause the greatest deviation from a physical $\Phi_{7\text{Be}}$ that is $\Phi_{7\text{Be}} \geq 0$. In the literature sometimes there is doubt cast on whether the Cl or Kamiokande experiment is correct. An extended model independent analysis is performed [8] (and somewhat less confining, because only the flux ratio $\Phi_{\text{B}}/\Phi_{\text{B}}^{\text{SSM}}$ and $\Phi_{7\text{Be}}/\Phi_{7\text{Be}}^{\text{SSM}}$ are fit, not the individual fluxes themselves.), and this has revealed

¹⁶In this report, various SSM's have been mentioned (BP, TOL, DFL). However, if the same input parameters are used all SSM's give similar predictions for the ν_e fluxes.

Figure 1.6: Confidence level curves in the $\Phi_B - \Phi_{7\text{Be}}$ plane for: a) Homestake(Cl) + GALLEX and SAGE combined (Ga) + Kamiokande(Ka) data, b) Cl + Ga data, c) Cl + Ka data and d) Ga + Ka 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.

that if the Cl experiment is completely neglected the fit is still separated in this parameter space, from the values expected by various SSM's, and non-standard solar models, to be discussed as the next solution to the SNP. If any two of the experiments are neglected, we are still left with the SNP. It should also be mentioned, that the GALLEX experiment has successfully calibrated their experiment in June 1994 with a ${}^{51}\text{Cr}$ ν source. The ratio of measured ${}^{71}\text{Ge}$ to the expected value, was calculated to be 1.04 ± 0.12 . This is the first test of the direct calibration of a solar ν experiment with a ν source. This emphasizes the reliability of the results of this experiment. The SAGE experiment has installed a similar source in December 1994, and the results are expected later this year[2].

1.4.2 Astrophysical Solutions

The solution proposed here, is that there is something wrong with our understanding of how the sun works (even though the current model correctly reproduces all the observable characteristics of the sun). One of the main quantitative predictions is that the ν fluxes are proportional to the temperature in the center of the sun (T_c) raised to some power. For example, it is predicted that in the SSM of Bahcall and Ulrich[1] the ν fluxes vary as, $\Phi_{\nu B} \propto T_c^{18}$ and $\Phi_{\nu Be} \propto T_c^8$. A class of solar models, known as non standard solar models (NSSM), suggest 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 flux to vary considerably (For example if the T_c is lowered by only 5% we get a $\Phi_{\nu B}$ flux with $(.95)^{18} \sim 0.4 \Phi_{\nu B}$ and similarly for the $\Phi_{\nu Be}$ the change would be by a factor of 0.65). Castellani et al.[9] also show that even with NSSM's, the ν fluxes still have this power law relationship, so that T_c can be a reasonable model independent parameter (see Figure 1.7)¹⁷. The problem qualitatively is that according to the SSM's, and the NSSM's, $\Phi_{\nu B}$ varies with a higher power law exponent than $\Phi_{\nu Be}$. However, we know that the experiments range from 0.3-0.5 $\Phi_{\nu B}^{ssm}$ and $\Phi_{\nu Be}$ is practically zero. So that the $\Phi_{\nu Be}$ 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!). Quantitatively, the same analysis as was done with $\Phi_{\nu Be}$ and $\Phi_{\nu B}$ can be performed with the power laws corresponding to each flux. A χ^2 fit is done as a function of T_c for all the solar ν experiments(see Figure 1.8). Here it is seen that the experiments still don't agree with each other, even if a power law fit is performed. So even a central solar temperature reduction can not explain the SNP.

¹⁷In Figure 1.7 various NSSM's are stated. Although the details will not be discussed, these models attempt to lower T_c by lowering various cross sections in the pp chain S_{17} and opacity of the sun, and by changing the assumed elemental composition (Z/X) and age of the sun.

Figure 1.7: The behaviour of Φ_{pp} , Φ_{7Be} , and Φ_B as a function of the central temperature T_c when varying S_{17} , opacity, Z/X and age, all of which are NSSM's

1.4.3 Nuclear Physics Solutions

The solution that is suggested is that the SNP may be resolved because of a possibility that the cross sections used as input parameters in SSM's are incorrectly extrapolated from terrestrial experiments to the solar environment. The quantitative predictions of the SSM are largely dependent on the cross sections for the nuclear fusion reactions of the pp-Chain, and the CNO Cycle. Thus, it is important to be confident of the values for the cross sections, and this can only be attained by extrapolating data from experiments to lower energies. It has been suggested that if the ${}^7\text{Be}$ proton capture reaction cross section (S_{17}) is lowered, it would suppress Φ_B ¹⁸. A fit to the solar ν experiments similar to Figure 1.8 has been performed [9],

¹⁸There is some recent experimental evidence that this cross section differs from the SSM input cross section by a factor of 2. [10]

Figure 1.8: The χ^2 as a function of the central temperature T_c for various experimental combinations. The notation is as in the previous figures.

where the ${}^7\text{Be}$ proton capture cross section is lowered well below what is suggested by recent experiments [10](see Figure 1.9). It is seen that the fit has become worse as compared to the case when the SSM value ($S_{17} = 22.5$ eV barn) for the cross section was utilized. This lower value for the cross section can be ruled out at the 99.99% C.L.

Another suggestion is that there exists a low energy resonance in the ${}^3\text{He}+{}^3\text{He}$ cross section. This would shift the terminations (see Figure 1.1) from PPII and PPIII (where the observable fluxes $\Phi_{{}^8\text{B}}$ and $\Phi_{{}^7\text{Be}}$ are) to PPI (which has no ν 's). The argument is, that the low energy resonance would be more efficient in the outer zone of energy production, and hence closer to where the $\Phi_{{}^7\text{Be}}$ flux peaks. This would mean that the ${}^7\text{Be}$ flux would be suppressed more than $\Phi_{{}^8\text{B}}$, because $\Phi_{{}^8\text{B}}$ peaks closer to the center of the sun where there is the highest energy production.

Figure 1.9: The χ^2 as a function of the central temperature T_c . In this figure the recently proposed value $S_{17} = 12$ eV barn is used.

If a χ^2 analysis is performed as a function of the resonance strength for different values of the energy at which the resonance occurs, then the best result $\chi^2 \sim 14$ still rules out this hypothesis at the 99.9% C.L.

A recent paper [11] has suggested that a combined effect of 2 processes, namely, a reduction in the cross section for the reaction, ${}^7\text{Be}(\epsilon^-, \nu_e){}^7\text{Li}$ by a factor of 2, and a resonance in the ${}^3\text{He}+{}^3\text{He}$ channel below 15 keV, would cause a reduction in $\Phi_{{}^7\text{Be}}$ by a factor of 8.6 and a suppression of $\Phi_{{}^8\text{B}}$ by a factor of 1.6. This recent model at least reduces $\Phi_{{}^7\text{Be}}$ more than $\Phi_{{}^8\text{B}}$. The author of [11] emphasizes that in particle physics solutions to the SNP (which will be discussed next) such as the Mikheyev-Smirnov-Wolfenstein Effect 2 free parameters are introduced to fit 3 experimental data points. We should at least allow ourselves the same amount of freedom in the nuclear physics sector to get closer to experimental results, but

without having to go beyond the Standard Model of particle physics.

1.4.4 Particle Physics Solutions: ν Oscillations

The solution proposed is that the SNP may be solved by the possibility that solar ν 's may change into an undetectable particles 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 idea is that the ν_e is a flavour eigenstate, but is not necessarily a mass eigenstate. Rather, ν_e is a mixture of 2 mass eigenstates ¹⁹. A simple way of understanding this, is to represent the flavour eigenstates $|\nu_e\rangle$ and $|\nu_x\rangle$ (ν_x refers to any ν that is not of the electron flavour, thus x could be μ or τ) as a mixture of 2 mass eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$:

$$\begin{aligned} |\nu_e\rangle &= \cos\theta_v |\nu_1\rangle + \sin\theta_v |\nu_2\rangle \\ |\nu_x\rangle &= -\sin\theta_v |\nu_1\rangle + \cos\theta_v |\nu_2\rangle \end{aligned}$$

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

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

So that if $m_1 \neq m_2$ than 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:

$$\begin{aligned} |\nu_e(t)\rangle &= \cos\theta_v e^{-iE_1 t} |\nu_1\rangle + \sin\theta_v e^{-iE_2 t} |\nu_2\rangle \\ |\nu_x(t)\rangle &= -\sin\theta_v e^{-iE_1 t} |\nu_1\rangle + \cos\theta_v e^{-iE_2 t} |\nu_2\rangle \end{aligned}$$

¹⁹The assumption of 2 mass eigenstate mixing is discussed only for simplicity. A full treatment must also include the 3 mass eigenstate possibility.

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

$$\begin{aligned} P_{\nu_e \rightarrow \nu_x}(R) &= \sin^2(2\theta_v) \sin^2[\pi R/L_v] \\ L_v &= 2\pi/(E_1 - E_2) \\ &= 4p\pi/(m_1^2 - m_2^2), \end{aligned}$$

where R represents the distance the ν has travelled in time t , and L_v is the vacuum oscillation length, dependent on the difference of the masses squared of the two ν mass eigenstates. Thus 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 thus become undetectable by the four existing solar ν experiments. The typical value for L_v may range from several tens to a few hundred metres. Thus if R is the distance from the sun to the earth, we may replace the $\sin^2$ term by its average value. So that we get:

$$P_{\nu_e \rightarrow \nu_x}(R) = (1/2) \times \sin^2(2\theta_v)$$

Now, if we assume maximal mixing ($\theta_v = \pi/4$) then the probability for flavour conversion is $1/2$. However, experience with the Cabibbo angle in the quark sector, suggests a small vacuum mixing angle, so that a solution to the SNP due to vacuum oscillations would be unlikely.

There is a possibility 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. The suggestion is that only the electron flavour ν may undergo this interaction, since an electron is created in the process, consequently for the corresponding interaction in the μ , or τ sector a heavy charged lepton would need to be created. Thus it is not possible for ν_x to undergo this interaction, since solar ν 's only have enough energy to create electrons. The importance of this interaction is that it singles out the ν_e 's, so that ν_e 's acquire an

additional phase. This means that the phase of ν_e may evolve differently from ν_τ as these ν 's travel through the sun. With the MSW mechanism, it is not required to make unreasonable extensions to the Standard Model of particle physics, and it requires no changes to the SSM²⁰. Thus, the MSW mechanism is perceived to be the most likely solution to the SNP. The result of this interaction is to introduce a new matter mixing angle θ_m , such that:

$$\tan(2\theta_m) = \frac{\tan(2\theta_v)}{(1 - (L_v/L_e) \sec(2\theta_v))}$$

$$L_e = \frac{2\pi}{\sqrt{2G_F n_e}}$$

Where L_e is the known as the ν_e -electron interaction length and n_e is the electron number density in the sun. The analysis is exactly the same as the preceding analysis with vacuum oscillations, except that θ_v is now θ_m . It is seen that there is a resonance when the denominator above vanishes, that is:

$$(L_v/L_e) = \cos(2\theta_v)$$

Thus regardless of the smallness of the vacuum oscillation angle, if the electron density through which the ν 's are travelling approaches the resonant density, then maximal mixing may occur. If the E_{ν_e} is greater than some value E_{min} (corresponding to the energy of ν 's when the the resonant density occurs in the center of the sun) then the ν 's will undergo maximal conversion.

$$E_{min} = 6.6 \cos(2\theta_v) (\Delta m^2 / 10^{-4}) \text{ in MeV}$$

When comparison is made with experiments, the results obtained are often presented as iso-signal contours on a $\Delta m^2 - \sin^2(2\theta_v)$ plot. All the present exper-

²⁰ ν oscillations do require ν 's to have mass, which is contrary to what is suggested in the Standard Model of particle physics. However, this assumption was put into the model as a consequence of experimental observation, not because it is an explicit prediction made by the model. Indeed many of the extensions of the Standard Model require ν 's to have mass.

iments exclude all areas in this parameter space, except two regions, (shown in Figure 1.10 ²¹ the large angle solution at $\sin^2(2\theta_\nu) \sim 1$, and the small angle mixing at $\sin^2(2\theta_\nu) \sim 10^{-2}$.)

Figure 1.10: The updated result of the combined MSW analysis assuming the Bahcall-Pinsonneault SSM with He and metal diffusion.

²¹Updated versions of this plot, and recent analysis can always be found at <http://dept.physics.upenn.edu/~www/neutrino/update1195>)

Every solution may correspond to different scenarios of ν_e propagation through the solar interior. For example, the small mixing angle solution corresponds to propagation where the adiabatic approximation no longer holds, that is the electron density is changing so fast, that a different analysis must be done. In this case, the survival probability (probability for a ν_e to remain a ν_e) depends on the ν energy differently than the adiabatic case, where a smooth flavour conversion occurs. For the non-adiabatic case, the survival probability P_e can be approximated by the Landau-Zener Approximation:

$$P_e = e^{-k/E}$$

Where k is a constant that depends on the change in electron number density and the two MSW parameters $\sin^2(\theta_m)$ and Δm^2 . Here it is seen that the lower energy ν_e 's are suppressed more than the high energy ν_e 's. This has the observational consequence of not only changing the shape of the ${}^8\text{B}$ ν_e spectra but also may allow us to distinguish the non-adiabatic solution from the large angle solution which suggests equal suppression for all ν_e 's with energies above a critical energy (see [12]). So if these distortions in the differential energy spectra can be seen, it would be clear evidence that ν oscillations exist, and would provide a way to explain the SNP. However, only the direct counting, real time experiments, would be sensitive to this effect, because these are the only experiments that can measure the ν_e differential energy spectrum.

Another possibility for an observational consequence of the MSW effect may be a day-night asymmetry in the ν_e flux detected. The suggestion is, that the ν_τ 's may change back to ν_e as they travel through the earth. Since, the largest distance solar ν 's travel through the earth is at night, it is expected that there is an increase of ν_e flux at this time. Unfortunately, the parameter space at which the highest day-night effect is observed, has already been excluded by Kamiokande II data [13]. However, future experiments such as SNO (described in the next section) will have higher statistics, and be sensitive to a wider parameter space.

1.5 The SNO Detector

It is clear, that to solve the SNP in a definitive way, a model independent experiment must be performed, to either discount, or accept the MSW effect. This is finally coming to fruition with the construction of the SNO, a detector that is not only sensitive to ν_e but will also be sensitive to ν_x . In this way, it may directly compare the ν_e and ν_x fluxes, coming from the sun, and thus determine if there is a deficit in the ν_e flux, due to flavour conversion. SNO is a direct counting, real time water Čerenkov detector (see Figure 1.11).

Figure 1.11: The SNO detector

SNO employs as its main active volume 1000 tons of 99.85% isotopically pure D_2O , and is situated in a specially excavated cavity 2.1 km below ground in a mine in Sudbury, Ontario. The D_2O is housed in a 5 cm thick optically transparent 12 m diameter acrylic vessel, itself immersed in 7300 tons of ultra-pure H_2O . The depth of the cavity (as will be discussed in the next chapter) ensures a low signal due to background induced by cosmic rays, and the H_2O surrounding the acrylic vessel shields the D_2O from backgrounds coming from the walls of the cavity. Surrounding the acrylic vessel are 9600 Hamamatsu Photonics (modified R1408 PMT's) 20.5 cm diameter photomultiplier tubes. Each PMT is surrounded by a reflector (made out of Omega aluminum), which not only increases the photocathode coverage to approximately 60%, but also protects PMT's from the light caused by radioactive decay in neighbouring PMT's. The cavity has within its walls an array of magnetic field compensation coils, that reduce the magnetic field so that the effect on the PMT's of the earth's magnetic field will be negligible. The entire SNO detector is optimized, so that it is sensitive to the Čerenkov radiation produced by electrons due to ν interactions with the D_2O . The SNO detector will measure about 10 PMT hits/MeV²², for an electron traversing the heavy water. The vertex of the initial ν interaction and the type of ν reaction can be determined by using timing information, and the location and pattern of the PMT hit distribution.

1.5.1 ν Reactions detected in SNO

Solar ν 's will interact with the D_2O active volume in three different ways, each giving independent information about the solar ν flux.

The CC ν Reaction

$$\nu_e + d \rightarrow p + p + e^-$$

²²A PMT Hit is defined as a detection of a photon by one PMT

This reaction will occur for any ν_e exceeding 1.44 MeV, and produces an electron which will have an angular distribution given by:

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

Where ϕ is the angle between the incoming ν_e , and the outgoing electron. Also the electron energy will be strongly proportional to the initial ν_e energy. As a result, the CC reaction will provide important spectral information about the ν_e , and may allow the detection of spectral distortion caused by the MSW effect discussed earlier. The latest prediction [14] of this distortion, taking into account the response of the SNO detector is shown in Figure 1.12.

Figure 1.12: The SNO CC spectrum expected for various MSW solutions.

Detection of the CC reaction will be facilitated by the Čerenkov radiation produced by the electron leaving the vertex. This reaction is also sensitive to the luminous ν_e emission in the first 0.1 s after stellar collapse, signalling the occurrence of a supernova. The count rate from solar ν 's interacting via the CC reaction is expected to be about 7 counts/day.

The ES Reaction

$$\nu + e^- \rightarrow \nu + e^-$$

This reaction is sensitive to all ν types,²³ and is the main detection reaction used by previous solar ν detectors, such as Kamiokande. Indeed, the strongly forward peaked electron, gives much directional information, and has historically confirmed that ν_e 's are emitted by the sun. This reaction is detected by the Čerenkov radiation produced by the forward going electron. Even though all ν 's may facilitate this reaction, the ν_e interaction cross section is 6 times higher than for other flavours, because this reaction may also occur through W exchange. The expected rate for the ES reaction is about 1 count/day.

The NC Reaction

$$d + \nu \rightarrow p + n + \nu$$

This reaction is completely flavour blind, and thus is sensitive to all types of ν 's. It is the main reaction that is unique to SNO in that rates measured by this reaction can be compared to the rates observed by the CC reaction. If a deficit in the ν_e 's

²³The NC and ES reactions are sensitive to ν_τ and ν_e but not the hypothetical sterile ν_s which do not participate in left-handed currents.

is observed in this ratio, it will confirm flavour conversion independent of astrophysical models. Furthermore, recent analyses have demonstrated the possibility of determining the validity of the MSW solutions, that have not been rejected by experiment, not only by analyzing the spectral distortion, but also by determining the CC/NC ratio. These results are shown in table 1.4,[14],[15]. The expected interaction rate of the NC in SNO (assuming a 100% capture efficiency) is about 12/day.

MSW Solution	Hata and Langacker 93	Bahcall and Krastev 95
Non-adiabatic	1.7→5	1.8→4.9
Large-Angle	3.3→5	3→6.4

Table 1.4: The theoretical range determined by two independent calculations of the $(CC/NC)/(CC/NC)_{asm}$ ratio of ratio's for two allowed solutions of the MSW parameter space.

The detection technique for this reaction is more complex than the other reactions, and deserves further explanation. The proton that is emitted from the vertex is immediately stopped without producing any Čerenkov light or scintillation light. Consequently, the only reaction product that may be detected is the neutron (n). Since, D₂O is such a good moderator, the n rapidly loses energy through scattering. On average, the n will travel 14 cm before coming to thermal equilibrium with its surroundings. Subsequently, the n will scatter at random, and may be absorbed by the D₂O or other additives such as MgCl₂. Upon capture, onto the Cl atom, high energy γ 's are released. These will Compton scatter and produce electrons, which in turn emit Čerenkov radiation which will be detected. Simple Monte Carlo calculations show, that the n capture process can be understood only by assuming a uniform distribution of ν events in SNO, and that the n is immediately thermalized, and starts a random walk. The capture efficiency calculated by this method, and other more sophisticated calculations, predict about 83% capture efficiency for MgCl₂ dissolved in the D₂O. One major disadvantage with this method, is that to determine the definitive NC signal, the detector must be cycled with the MgCl₂

in and out, for equal times, so that the rates may be subtracted. This means that the duty factor for the NC detection is 50% of what it would be if the NC additive is left in the D_2O . Another problem with this method of NC detection is that there are multiple γ 's produced, and many will not have enough energy to produce electrons above Čerenkov threshold. Thus a second NC detection method was proposed, involving discrete charged particle counters that are distributed throughout the D_2O active volume.

The difficulty with the discrete counters 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 n 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 will produce charged particles that may masquerade as n capture. Investigation of this contamination has suggested that these events can be separated from n capture events by pulse shape discrimination. The capture efficiency for this method is expected to be much less than the dissolved salt technique at about 45%. The expected interaction rate of the NC in SNO (assuming a 100% capture efficiency) is about 12/day.

A significant background to the NC reaction, arise from γ 's that have an energy exceeding 2.223 MeV, so they may photo-disintegrate a deuteron, and thus produce a free n. These backgrounds will be discussed in the next chapter. It must be mentioned, that if better CC to NC signal separation can be done, it is not necessary to cycle the salt in and out of the D_2O . This is the main disadvantage of the dissolved salt technique, and so reduces the need for the 3He counters method. Recent studies [16] have shown that it may be possible to do virtual on-line separation of these events, so that the need for the discrete counter technique is questionable.

1.5.2 Calibration of SNO

The SNO Collaboration utilizes several techniques for calibrating the response of the SNO detector. First, to determine the optical properties of the detector a N_2 laser connected to a diffuser ball will be used. Various sources for high energy (5-20 MeV) calibration have been proposed, and are currently being developed. Low energy calibration (≤ 5 MeV) will be performed by using a proportional counter, with β emitters that occur naturally throughout SNO, deposited on the anode. The β is tagged by the proportional counter and the subsequent Čerenkov radiation that is produced, can be detected by the sphere of SNO PMT's. In this way, the response of the SNO detector to various backgrounds present can be determined independently. The presentation of the results of an experimental investigation of this technique, (to be described later in Chapter 3) is the main purpose of this report.

Chapter 2

The Backgrounds Present in SNO

2.1 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 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. For completeness, the cosmic ray background will be discussed below. It is expected however, that this 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 24 muons/day will pass through the active volume of SNO (MARK I, the initial design of SNO estimates [17]). A more troublesome form of the background, is the inevitable Th and U that is present in the detector components themselves. Indeed, this is the main challenge to the SNO Collaboration, to construct the detector out of materials whose activity is low enough to make the signal to background ratio acceptable. The signals due to the background caused by activity in the detector components form the remainder of

this chapter.

2.2 Cosmic Ray Backgrounds

Since the SNO detector is built 2.1 km below the ground, only the cosmic ray muons and ν 's survive. It is easy to discriminate the muon signals from other signals expected, because muons have much higher energies than electrons produced by nuclear decay of components in the detector, or of solar ν 's. For example, a muon that does not interact with the active volume at all, but passes straight through, will leave about 30000 PMT hits distributed over the area of a circle (or ellipse depending on the muon trajectory). It will also leave several PMT's completely blinded by a muon which passed nearby as it travels out of the SNO active volume. A muon may also in some cases interact with the D_2O (about 6% of the time for MARK I) producing spallation products that can be detected. When a muon interacts with the ^{16}O it can produce 8B which after 0.7 s will β -decay and produce a high energy β (13.7 MeV) which will then be detected. Similarly ^{12}B and ^{12}N may be produced, which after several tens of ms will also decay and give a high energy β (16.4 MeV for ^{12}N and 13.4 MeV for ^{12}B). In addition to these products, the initial muon interaction may also produce free n's, which will be captured, and produce a signal masquerading as a NC ν . This is not expected to be a serious NC background, because it is in delayed coincidence with the high energy muon signal.

2.3 Detector Component Backgrounds

Since the signature for the ν interactions is the Čerenkov photons produced directly by β 's, and indirectly by the γ 's, any process that produces Čerenkov photons comparable to this, will be a source of background. Consequently, the main source of background for SNO is that due to the Th and U, which are present in the materials out of which the detector is constructed. The main contamination comes from β 's and γ 's in the ^{232}Th and ^{238}U chain (shown in Figure 2.1. and Figure 2.2).

Figure 2.1: The ^{232}Th Chain

The effect of the activity on the detector response is that the background increases exponentially toward lower energies. This ultimately fixes the threshold for the detector. In addition, any γ that has an energy greater than 2.223 MeV may photo-disintegrate the deuteron, and will appear as a NC signal. The primary isotope producing this background is ^{208}Tl at the bottom of the ^{232}Th chain, which produces a 2.615 MeV γ 36% of the time a ^{212}Bi decay occurs. In the ^{238}U chain ^{214}Bi produces a 2.445 MeV γ , but this is not expected to be as serious a background as that due to ^{208}Tl decay, because this reaction will only occur 1.54% of the time a ^{214}Bi decay occurs. See Figure 2.3 for the details of the decay schemes of these isotopes.

The events reconstructed in one year of operation, due to the presence of Th and U, in the various materials out of which the detector is constructed, is displayed in Figure 2.4. The expected signals due to the CC, NC and ES are also shown in Figure 2.4. From this, it is apparent that it is required to set the detector

Figure 2.2: The ^{238}U Chain

low energy threshold at about 5 MeV which corresponds to 50 PMT Hits. The individual background due to each reaction will now be described.

2.3.1 Summary of the Backgrounds to the ν Detection Reactions

ES Reaction Background

The ES reaction produces electrons which are strongly forward peaked, so that the Čerenkov ring that will be projected on the PMT's will have the reconstructed vertex and the centre of mass¹ of the PMT distribution in the sun-earth direction. The background to this reaction is any β which produces the same number of Čerenkov photons, and is also travelling parallel to the sun-earth direction. This

¹Centre of mass of the PMT distribution is defined as the calculated centre of the Čerenkov ring.

Figure 2.3: Simplified decay schemes for ^{212}Bi and ^{214}Bi -adapted from STR-87-12

background can come from β 's and γ 's from Th and U in the D_2O and other detector components. The CC reaction is also a background, because this reaction occurs an order of magnitude more often, and produces electrons of a similar energy, which may also go forward within the kinematic constraints imposed by the ES reaction. A separate measurement of this reaction may be made independent of the CC reaction with light water as the active volume. The detector is sensitive to the ES reaction in about 1645 tonnes of H_2O . Of this volume, only 600 tonnes is in the PMT field of view. This fiducial cut does decrease the number of reconstructed events. However, its insensitivity to the CC will allow about 680 events to be reconstructed outside the acrylic vessel in 3 years above a 50 hit threshold² (see [18]). It should be noted that some of the CC and NC events will reconstruct outside the acrylic vessel. Nevertheless, by imposing a fiducial cut so that the inner radius of the active volume of the H_2O is decreased, this background will be also decreased.

²It is assumed that the ν_e flux is as predicted by the SSM

CC Reaction Background

The CC reaction produces electrons that have an energy almost exclusively of $E_e \sim E_\nu - 1.44$ MeV. Consequently any β 's and Compton scattered γ 's that produce Čerenkov photons will produce a detectable background. These will come from the detector components, and will be discussed below. In addition high energy γ 's produced by n-capture on the NC additive to the D_2O , will Compton scatter, and produce Čerenkov photons, which will be difficult to separate from the CC signal. Studies are in progress of CC PMT patterns (see [19],[16]), and may offer ways to distinguish these from the NC signal³.

NC Background

As was mentioned, the NC is detected by n-capture on $MgCl_2$ or in the 3He counters. In each scenario, any free n that is produced will be a detectable background to the NC. In addition, in the case of the $MgCl_2$ additive any γ of a comparable energy to the 8.6 MeV γ released in n-capture on chlorine, is a potential background. These can be γ 's produced by $(\alpha, p\gamma)$ and by (α, n) followed by (n, γ) reactions. However, many of these γ 's will come from the rock surrounding the detector, and Monte Carlo simulations [22] have shown that only the γ 's crossing the Photomultiplier Support Structure (PSUP) sphere radially inward generally make it to the D_2O . Consequently, many of these high energy γ 's that are not due to the NC signal can be identified. Another troublesome background is any γ with an energy above 2.223 MeV, since these will photo-disintegrate the deuteron once in a few hundred collisions. There is a possibility to discriminate the photo-disintegration background from the NC signal by using a 16ms look-back window (4 n capture times) to look back in time for a β before the reconstructed vertex of the n capture. Unfortunately, any β that occurs within this 16 ms look-back window will appear as a NC

³There is some evidence for the possibility that the CC electron will produce two Čerenkov rings some of the time instead of one as was previously thought (see [20]). Further confirmation came from simulations of electron tracks using EGS4 (Electron Gamma Shower Code) [21]. However, it is unclear in the latter study whether the effect is an EGS4 artifact, or a true physical phenomena. More investigation will be done to study this.

background. It is shown by Monte Carlo calculations [23] that using this 16 ms look-back window technique, the n background can be determined for all detector components as long as the vertex of the β can be reconstructed. The decision for having MgCl_2 as the NC additive, instead of NaCl as had been initially planned, has further eliminated the background. This is due to the 2.754 MeV γ that is produced by n activation on ^{24}Na present in the piping to and from the acrylic vessel. This does not change the n capture efficiency, or the signals expected by the NC interaction.

2.3.2 Summary of the Backgrounds from 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 and U in each component out of which the detector is composed. Each component has its characteristic shape in the response of the detector, and thus by employing various cuts (fiducial and otherwise) in the analysis many of the backgrounds present in the data may be reduced. The detector response due to the activity present in each detector component is shown in Figure 2.4.

Cavity and Rock Surrounding the Detector

One of the principal reasons for choosing the particular site for the SNO detector was the low activity (3.3 ppm Th, 1.2 ppm U) of the Norite rock surrounding the cavity. Since the amount of Norite (and thus the activity from the Norite present at the SNO site) can not be changed, only by shielding the detector from the rock by light water surrounding the PSUP have 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 D_2O . The high energy γ 's however, that are created by $(\alpha, p \gamma)$ and by (n, γ) on light elements in the rock, may make it past the PSUP and be reconstructed inside the active volume of SNO.

SNO Detector , D₂O + NaCl

Figure 2.4: The Monte Carlo prediction for the events reconstructed due to various detector components in one year of operation of the SNO detector. The spectrum expected due to the CC, NC and ES reactions is also shown.

Simulations were done to track these γ 's [22] to the PSUP and study where these reconstruct. It was found that only the γ 's which cross the PSUP sphere pointing towards the center of the acrylic vessel, will in general make it to the D_2O . In this study, it was also found that 90% of the γ 's produced in the rock that make it to the D_2O come from the waist region (defined as the region 4.5m above and below the equator). This is where there is the least amount of shielding because of the proximity of the D_2O to the cavity wall. The flux expected to be reconstructed within the D_2O is 0.11 γ 's/day above 5 MeV. Of these events, only 0.04 γ 's/day reconstruct within a 550 cm radius. So, if an outer radius cut is imposed for the NC measurement, many of these high energy γ 's will not reconstruct inside the fiducial volume.

PSUP and the PMT's

The PMT's are supported on the PSUP, which is constructed of a stainless steel (~ 10 ppb Th/U) geodesic structure. Early simulations have shown [24] that about 14 γ 's/day are released into 4π . A more pervasive background is the Omega reflector and the PMT base itself. The Omega reflector will produce at least an order of magnitude higher background than any other PMT component. Later simulations suggest that about 117 γ 's/day have an energy above 5 MeV and are released isotropically. It should be mentioned that, as opposed to γ 's coming from the rock that are all pointed inward, these γ 's are released into 4π .

The radial distributions of the cavity γ 's and PSUP γ 's are shown in Figure 2.5. In Figure 2.5 it is clear, that at increasing radii (corresponding to a larger volume shell), the number of events reconstructed actually decreases; this is because the reflectors that support the PMT's shield the γ 's from other adjacent PMT's. It has been shown [25] that, based on simple arguments, only 1 γ 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 has led to the development of a new fitting technique, called the Quad Fitter, that can discriminate against mis-reconstructed events. The Quad Fitter, employing special cuts, has

Figure 2.5: An approximation to the simulated spectrum found in STR-94-13 showing the decrease of γ 's reconstructed, beyond a radius of 700cm

demonstrated that of 10^5 events generated only 105 events reconstruct inside the acrylic vessel (none reconstruct inside a 4m radius). It has been demonstrated that if a fiducial cut of a 3m radius is imposed, the background from the PMT β 's and γ 's are entirely removed above 2 MeV [26]. In the final analysis it is expected that the PMT's and reflectors will contribute about 0.3 n's/day in the D_2O [22].

Internal Backgrounds

The main sources of internal backgrounds⁴ are the Th and U which are present in the H_2O , acrylic vessel and D_2O , as well as the ^{40}K present in the D_2O . These backgrounds are unique in the sense that all the internal components are in the

⁴The internal background is defined as the background due to the Th and U in the H_2O , acrylic vessel, and D_2O .

field of view of the PMT's, and so not only γ 's, but also β 's, will be observed. This constrains the amount of Th, U, and ^{40}K that may be present in these internal materials. The concentrations tolerated by the SNO Collaboration are shown in Table 2.1 for the H_2O , acrylic vessel and D_2O .

Component	Mass(10^3 kg)	Th(g/g)	U(g/g)
D_2O	1000	11.E-15	11.E-15
H_2O	1667.7	22.E-15	15.E-15
Acrylic	30.0	1.9E-12	3.6E-12

Table 2.1: Masses and concentration of ^{232}Th , ^{238}U in internal detector components

The background due to the internal detector components expected from the ^{208}Tl γ is about 3 n/day⁵. The corresponding background due to the ^{214}Bi 2.445 MeV γ is much less of a problem at 0.26 n's/day. The events due to the background in the D_2O are expected to be reconstructed uniformly throughout the D_2O active volume for PMT thresholds above 40 hits [22]. It is tolerated that the concentration of the H_2O may be considerably higher than D_2O , because not as many of the γ 's produced in the H_2O will be reconstructed within the D_2O active volume. Monte Carlo simulations have demonstrated that about 0.14 n/day are expected due to the H_2O . By far the highest internal background comes from the acrylic vessel, about 6.49 n's/day. Radial distributions show that, if higher PMT thresholds are imposed, the background in the acrylic region dominates. This is because of the small amount of light attenuation in the D_2O , so that hardly any high energy γ 's interact until they approach the acrylic vessel. Finally, the other components such as the ropes will contribute about 0.3 n/day.

⁵It should be mentioned that these numbers are assuming that the Th and U are in secular equilibrium. However, chemical processes may change the amount of Ra in the D_2O and will change the ratio of the amount of Ra to parent Th or U from the value at secular equilibrium. When there is secular dis-equilibrium the number of high energy γ 's will vary from that calculated at equilibrium.

2.3.3 Discussion

From the preceding analysis, it is apparent that to do an accurate measurement of the CC/NC ratio, the low energy backgrounds that are present must be very well understood. Also, the spectral distortion due to the MSW effect is most evident in the low energy region of the spectrum. For these reasons, it is necessary to have a good technique for energy calibration, to know exactly the shape of the background wall. The technique discussed in the remainder of this report, will allow a measurement to be made of the shape and amplitude, of all the main contributors in the ^{232}Th and ^{238}U chains to the SNO background. The current study focuses on the determination of the rates and spectra of various isotopes in the ^{232}Th chain. However, the technique will also be applied in the future to isotopes in the ^{238}U chain.

Chapter 3

The Testing of the Proportional Counter Source

3.1 Introduction

As has been emphasized in the previous chapters, it is imperative that if a clean measurement is to be made of the CC/NC ratio, and the CC spectral distortion, the low energy background in SNO must be very well understood. For this reason a technique has been developed, so that each component of the background produced by various isotopes in the D_2O , can be assessed. The technique relies on a proportional counter source (PCS), which acts both as a detector, as well as a source. Various sources such as ^{228}Th (the source used in this first stage of testing the method) are placed on the anode of the proportional counter. When a β is emitted by the source, it is tagged by the PCS, and the subsequent Čerenkov radiation that is produced by the electron upon travelling through the D_2O , is detected by the surrounding sphere of SNO PMT's. The PCS signal that is produced due to the β , will send a pulse to the global trigger of SNO, so that the signal in the SNO PMT's can be observed. Using this coincidence technique, the signals are looked at in a very small time window, (less than several hundred ns) and thus the backgrounds to these measurements are rejected.

Several stages of testing the technique are to be carried out, which in principle simulate the environment, and conditions present in SNO. The first stage of testing the technique, the subject of this report, involves a cylindrical tank (called the Čerenkov Cell) and two PMT's (see Figure 3.1).

Figure 3.1: Diagram of the Čerenkov Cell: not drawn to scale and the second SNO PMT not shown.

Later stages of testing will involve testing the technique at the University of Washington test facility, which is a sphere of 128 PMT's suspended in a pool of light water, used for testing the SNO data acquisition system.

3.2 The Prototype PCS

The detector used as a radioactive source, is a 2 cm long proportional counter with a radius of 1.1 cm providing an active volume of about 7 cm^3 (see Figure 3.2 for a diagram of the proportional counter).

Figure 3.2: Diagram of the PCS.

The cathode is a 0.018 cm thick Aluminum cylinder. The active volume is housed inside an acrylic tube 1.6 mm thick, which adds approximately 10-15 Čerenkov photons to the Čerenkov signal expected from a relativistic β traversing light water. The anode in the prototype is a 25 micron thick stainless steel wire, on which a ^{228}Th source is deposited. The gas used in the PCS is P10 (90% Ar, 10% Methane) which is extensively used in proportional counters for its ability in providing good resolution and electron multiplication. The gas is continuously flowed through the

proportional counter at a rate of about 14 cm³ per minute. The pressure in the detector is about 1 atmosphere. The optimum voltage applied to the proportional counter so that the β 's do not saturate the pre-amp, but still provide a fast rise-time in the proportional counter, was found to be 1780 V. At this voltage the electric field and the gas produce a multiplication factor of approximately 8000. As the β travels through the gas, it ionizes the gas, producing about 90 primary electron pairs/cm for a minimum ionizing β . For the combined multiplication factor, capacitance in the detector, and pre-amp gain, a signal for the β 's of several hundred millivolts are expected. (An in depth analysis of how proportional counters work is beyond the scope of this discussion, and the reader is referred to F. Sauli's excellent monograph on the theory and operation of proportional counters [27]). The PCS is constructed so that a very small fraction of the β energy is deposited (1% of the β energy) in the proportional counter, just enough to be able to tag the β but not to significantly affect the β energy spectrum. The signal and the high voltage are carried through the same cable, and the signal is extracted using a direct current blocking capacitor, and sent to the pre-amp for further amplification. The aim is to be able to develop a triggered source that will approximate as closely as possible the same source, without the detector surrounding it. The issues for improving the prototype design in the next stage of testing the PCS will be described in the next chapter.

In the operation of the detector one major problem was encountered. This is the scintillation due to the electron avalanche at the anode, because it has enough kinetic energy to excite the Argon gas¹. This is a problem, because the amplitude of the scintillation light is much higher than the signal due to Čerenkov light and the signal is in coincidence with the PCS. . Thus, it is hard to extract the Čerenkov signal from the sum of Čerenkov and scintillation light (which is the signal observed). The fact that the signal observed is in coincidence with the PCS, suggests that the source of the light is the PCS. Various tests have been performed

¹The quench gas added to the Argon is not enough to absorb all the photons so that scintillation light is still visible

to verify that the light is real, and not due to an electronic effect. Each PMT separately has been covered with dark plastic and subsequently the signal in each PMT was observed. It is seen that the signal observed by a covered PMT, has decreased to 1/10 of the amplitude seen in the uncovered PMT. This proves that the light is exterior to the PMT, and is not an electronic effect. Next, to test the hypothesis that the source of the light is the PCS, the proportional counter was covered using aluminum foil and dark plastic. It was observed that the amplitude of the light as observed by the two PMT's decreased by two orders of magnitude. Thus, this taken together with the fact that the first test proved that the source of light was external to the PMT's, proves that the source is the PCS. The assumption that the light is due to scintillation of the Argon gas within the counter is proven by its long time scale, large amplitude of the pulses due to electrons drifting through the electric field. To decrease the scintillation light so that none is detected, several steps were taken. First, the cylinder in which the counter is housed is covered on the inside with an opaque reflective² paint. As a result the scintillation light is not transmitted through the acrylic sleeve. Next, the thin acrylic endcaps that constrain the active volume, were covered with black paint, to further prevent scintillation light (at the source) from going toward the endcaps. Since the PCS is suspended vertically inside the Čerenkov Cell, it is particularly important to ensure that the light that goes towards the endcaps does not get out, because this is in direct line with the PMT's (see Figure 3.1). To further prevent light from escaping in the endcap region, the cylinder was covered on each end by an opaque, stretchable plastic that fit tightly around the cylinder, and around the cables that lead toward the PCS. Finally, the gas cables themselves were covered with aluminum foil, since some of the light may multiply reflect and travel through the gas line which runs adjacent to the PMT's. After these steps were taken, no scintillation light was observed.

²Reflective, so that the counter is not absorbing the Čerenkov light exterior to the detector.

3.3 The Čerenkov Cell

The PCS is placed vertically in a cylindrical tank 1.5 m length, and 30 cm in diameter called the Čerenkov Cell. The detector is held in the centre of the tank, by steel wire, which keeps it in place. Surrounding the detector active volume is a 2 cm acrylic shell, which acts as a Čerenkov source, allowing all the electronics to be set up without having the added complications produced by the addition of water to the Čerenkov Cell. At 40 cm's from the source on each side (vertically) of the proportional counter is a PMT, identical to the ones used in SNO. These simulate the sphere of 10000 PMT's surrounding the D_2O active volume.

The PMT's are Hamamatsu Photonics R1408 PMT's which have the bases modified to suit the requirements in SNO. The particular PMT's used in the Čerenkov Cell have been tested extensively at Queens University, and have been accepted as PMT's suitable for SNO. The single photoelectron spectrum is shown in Figure 3.3 for the top PMT, and in Figure 3.4 for the bottom PMT in the Čerenkov cell. Here it is seen that the single photoelectron peaks are visible above

Figure 3.3: Single photoelectron spectrum for the top PMT.

the noise for both PMT's. The discriminator threshold for the PMT's are set at 0.25

Figure 3.4: Single photoelectron spectrum for the bottom PMT showing the 0.25 single photoelectron cut-off.

of the single photoelectron peak (see Figure 3.4). The noise rate at this setting was 2000 Hz for the top PMT, and 9000 Hz for the bottom PMT, due to the wide single photoelectron peak for this PMT. The signal from the two PMT's are observed only in coincidence, so that the noise is rejected. Because of the excellent timing of the SNO PMT's, the coincidence window for the PMT's is less than 60 ns. As such, the two PMT's are treated essentially as one detector. This, in coincidence with the time that it takes for a β to trigger the lower level discriminator in the PCS, ensures a triple coincidence window of less than 100 ns³. The cylindrical tank is coated on the inside with Aluminum, so that the effective photocathode coverage is increased, thus the maximum amount of Čerenkov light is detected.

A Monte Carlo program (CERCELL.f) was written to simulate the geometry of the Čerenkov cell. It will be described in detail below in the discussion of the efficiency of the geometry of the Čerenkov cell.

³There are strict timing requirements by the SNO data acquisition system, which necessitate the coincidence window to be less than 180 ns [28].

3.4 The Experiments Performed

3.4.1 The Events Observed in the PCS

To determine the rates and spectra of the isotopes in the ^{232}Th chain and ^{238}U chain, various isotopes may be placed on the anode of the proportional counter. The current investigation reports results using ^{228}Th as the source deposited on the wire. This isotope will decay to ^{212}Pb , emitting four α 's. The ^{212}Pb will then decay to ^{212}Bi with an eleven hour half life. Many of these β 's are below the Čerenkov threshold so that they will not be observed by the PMT's.(refer to Figure 3.5)

Figure 3.5: Abbreviated ^{232}Th chain showing isotopes relevant to the current study.

^{212}Bi decays via two branches, a 36% α decay branch to the 3.1 minute ^{208}Tl nucleus, and a 64% β decay to the 300 ns ^{212}Po nucleus. Both branches finally decay to stable ^{208}Pb . As has been described in previous chapters when ^{208}Tl decays, a 2.6 MeV γ is released which may photodisintegrate a deuteron in the D_2O , and produce a free n, which cannot be distinguished from a free n produced by a NC ν interaction. Thus, it is very important to be able to determine exactly how much ^{212}Pb is in the D_2O , since this is the main background to the NC ν measurement. This can be done with the PCS by observing the delayed coincidence in the β - α cascade when ^{212}Bi decays to ^{208}Pb via ^{212}Po with a half life of 300 ns. Thus, the signal observed in the proportional counter due to the 64% branch of the decay of ^{212}Bi is a low amplitude β followed several hundred ns's later by a high amplitude α saturating the pre-amp of the PCS⁴. Thus, the electronics can be set up to select the delayed coincidence events and then to look back in time for the Čerenkov signal in the PMT's. The other events observed in the proportional counter are the events when just the α 's are seen, that is, the α 's that are observed due to the series of decays of ^{228}Th to ^{212}Pb , and the α that is observed due to the 36% branching decay of ^{212}Bi to ^{208}Tl . The third type of event that is observed in the proportional counter are the β 's that are observed with no α present. These are due to the decay of ^{212}Pb to ^{212}Bi , and the β that accompanies the 2.6 MeV γ in the 36% branching decay of ^{212}Bi .

To summarize, all the events observed in the proportional counter can be classified into three classes: the events where just the β is observed (the Just- β events), the events where just the α 's are seen (the Just- α events) and the delayed coincidence events (DC events). The isotopes that are assessed for the 3 different types of events, with and without demanding a coincidence of the PCS with the PMT's, are summarized in Table 3.1. It must be mentioned that event types like the Just- β or Just- α , are not purely β 's produced through β decay, or α 's produced through α decay. Rather it is the sum of all the events which satisfy electronic criteria (to

⁴This is because the α produces three orders of magnitude more primary electron-ion pairs than the β .

be discussed later) which classify the event as a Just- β or Just- α event. For example, a low energy α may be classified as a Just- β event, even though it is an α . See Table 3.1 which summarizes the main isotopes of sensitivity for each event classification.

Event type classification	main isotopes of sensitivity and particle(s) detected
Just- β	^{212}Pb , ^{212}Bi , ^{208}Tl β 's
DC	64% ^{212}Bi β 's
Just- α	^{228}Th , ^{224}Ra , ^{220}Rn , ^{216}Po , 36% ^{212}Bi α 's
PCS+(2)PMT+Just- β	^{208}Tl and ^{212}Pb β 's above Čerenkov threshold
PCS+(2)PMT+DC	64% ^{212}Bi β 's above Čerenkov threshold
PCS+(2)PMT+Just- α	64% ^{212}Bi β 's above Čerenkov threshold

Table 3.1: Summary of the event types and how these relate to the determination of the main isotopes in the ^{232}Th chain.

3.5 The Electronics and Experimental Set-Up

The main purpose of the electronics is to classify each event into one of the three classes described in the previous section with a high degree of efficiency, and good timing. After the event has been classified the next purpose of the electronics is to look back in time for a coincidence between both PMT's at the time the β has been observed in the proportional counter. When these triple coincidence events occur, the electronics must be able to record the spectrum observed in the PMT's, and the rate that each event occurs. The next section describes how the electronics was set up so that these objectives are met. A full electronic diagram showing the decision making logic, and the coincidence logic, is shown in Figure 3.6.

3.5.1 Event Classification Techniques

Method1: Electronic Decision Making (EDM)

To make the decision of what type of event has been observed by the proportional counter, various techniques have been employed. The technique relies on two main assumptions: the lower level discriminator (LLD) will fire immediately when a β or α is seen in the detector, and the upper level discriminator (ULD) is set so that it will fire when an α is observed (see Figure 3.7). The LLD fires on a highly amplified

Figure 3.7: Figure showing in part a) a DC event as observed by the PCS, and in part b) how DC events are electronically selected.

and differentiated β pulse. This ensures that the timing is as precise as possible. The ULD is fired on the second differential of the original β pulse coming out of the pre-amp connected to the PCS. This is because the second differential discriminates the low amplitude events from the higher amplitude events more clearly than the

first differential. Care must be taken that the timing filter amplifier which performs the amplification and electronic differentiation of the signals, does not differentiate on the rise-time of the particles seen in the detector. Since, if the differentiation time constant of the timing filter amplifier is set too short, the ULD would not fire for slow rise time α 's.

To make the decision whether a Just- α event has occurred, it is necessary to measure the variation in the rise-time of the β and α . This can be done, ¹ using a QVT Multi-channel Analyzer in T-mode. In this mode, the time difference between two NIM (the logic pulses used in nuclear instrumentation modules) pulses are digitized and recorded. In order to measure the variation of the rise-time of the β , and α ², the LLD is the start pulse to the QVT, and the ULD is the stop pulse (see Figure 3.8). From this analysis, the time spread of the rise time of the

Figure 3.8: Figure showing part of the time spectrum of the LLD and the ULD and thus the rise-time of the α . The calibration is ~ 8 channel/ns.

particles was found to be about 150 ns. Thus, the method used to determine if an event should be classified as a Just- α event, is that if the ULD fires within 250 ns

²It is really the rise time of the α that is being measured here, but since it is possible to have a fast β and slow α , it also measures simultaneously the spread in rise-time of the β .

(τ_{cut} in this report) of the LLD, then the event is classified as a Just- α event. This is furnished by sending a 250 ns NIM pulse into a coincidence unit (C-JA1) and waiting for a short ULD pulse. If the coincidence unit responds by firing a NIM pulse, it is recognized as a Just- α event(see Figure 3.9).

Figure 3.9: Figure showing in part a) a Just- α event as observed by the PCS and in part b) how Just- α events are electronically selected.

To determine whether an event observed in the proportional counter is a DC event, a similar method is employed. Here the LLD pulse is delayed equal to the time of the coincidence window in classifying the Just- α events (τ_{cut}). After the pulse is delayed, a 5000 ns ($16 \text{ }^{212}\text{Po}$ half lives, t_m in this report) NIM pulse is fired, and sent into a coincidence unit (C-DC1). During this time if a DC event has occurred, the ULD will fire, and the coincidence unit will respond by firing a NIM pulse signifying a DC event. Thus, by delaying the 5000 ns NIM pulse equal to the rise-time of the α (τ_{cut}), one can be sure that no Just- α events are mis-classified as

a DC event.(refer to Figure 3.7)

Finally, the last method is used to determine if the events are Just- β events. This is done by assuming that any other event that is not a Just- α or a DC event, must be a Just- β event (see Figure 3.10). Electronically this is achieved by vetoing any signal classified as a Just- α or DC event. Consequently, the events that are not

Figure 3.10: Figure showing a Just- β event as observed by the PCS.

vetoed, are the Just- β events since these are the only type of events that are left. It should be mentioned, that this is the most inaccurate rate measurement. This is, because if there is a problem with either the DC or the Just- α measurements, this will manifest itself in the Just- β event rate. Although the event decision making for the Just- α and DC occurs less than 50 ns after the ULD has fired, the decision making for the Just- β type event occurs much later. This is because it is necessary to delay the LLD pulse longer than the longest separated DC event, to ensure that these may still be able to veto the coincidence module (C-JB1) that tells us if a

Just- β event has occurred⁶. This complicates the recording of the β spectrum as observed by the PMT's since this requires the PMT Čerenkov pulse to be delayed of the order of several thousand ns until after the Just- β event classification decision has been made⁷.

Method2: Computational Decision Making (CDM)

At this point it becomes necessary to describe another technique for event classification which was used at a late stage in this investigation. The technique works by taking the PCS signal directly out of the pre-amp, and connecting it to one of the channels of a digital recording oscilloscope (see Figure 3.6). The oscilloscope is then triggered just above the noise. The digital oscilloscope can then be put into a mode where the time of occurrence relative to the trigger, and the amplitude and times, of an event can be written to a file. In this way all the information that is possible to be attained from the PCS is preserved. Once the event has been recorded, the event can be analyzed with similar criteria outlined in the EDM technique. A FORTRAN program (CDManalys.f, included in the Appendix) was written to classify each event as belonging to one of the various event types, just as is done with the EDM technique. For example, an artificial ULD is imposed by just setting in the program a voltage threshold, which considers the pulse an α when the pulse amplitude exceeds this value, and a β when it does not. The only difference in the criteria for the event classifications as compared to the EDM technique, is that the DC events do not require an α which is above the ULD setting. This requirement is relaxed so that various investigations can be performed, as will be described later in the results (see Figure 3.11 for an example of a CDM selected DC' event).

A complication in the analysis is that the oscilloscope's ADC has only 2⁹ chan-

⁶As a consequence of the finite amount of equipment available, it requires one to use ones ingenuity. In this case the signal from the LLD is sent into both inputs of a coincidence unit. In this way the coincidence unit will always respond when the LLD fires and since this is one of the only modules which has the veto option, this unit can be utilized.

⁷This is the reason why in the photoelectron spectra for both PMT's the second photoelectron peak is not clearly visible, because some resolution of the peaks is sacrificed since a second amplifier (Ortec-440A) with a delayed output is utilized.

Figure 3.11: Figure showing a DC event as selected by the program CDMAnalysis.f. The arrows correspond to the times determined by the program of the start of the β and α .

nels. Thus, if a low amplitude event (for example, a 35 mV β) is observed, then it can not be distinguished above background if the voltage range specified in the oscilloscope is 5 V. This is because the lowest possible amplitude is 50 mV (see Figure 3.12 for an example of a β event that can hardly be seen if a high voltage range is chosen). Also, if a voltage range of 100 mV is chosen, and a 1.5 V α is seen in the oscilloscope, the pulse will saturate the oscilloscope. It is thus necessary to observe the event in as many possible voltage ranges, so that all events can be classified.

It should be mentioned that the CDM technique does not by-pass all the electronics, since it is still required to determine whether a 2PMT coincidence has occurred. The logic for this is described in the next section. All that is required, is a coincidence between the 2PMT coincidence NIM pulse and a LLD pulse, since the determination of what event type it is, is done computationally. The simplicity of this technique, and the fact that it is not dependent on various experimental uncertainties that are difficult to gauge, make this method superior to the EDM technique.

Figure 3.12: Figure showing in part a) a Just- β pulse in the range at which the pulse height can be accurately calculated, and in part b) the pulse at a lower gain where the pulse can be hardly distinguished above background. The arrow signifies where the program C'DManalysis.f calculated the start of the event.

Consequently, this technique will be utilized in the future, and all calculations of the rates presented in this report are done using this method.

3.5.2 Setting of the Triple Coincidence and Recording the Spectra

As was mentioned before, the second purpose of the electronics is to select the events in the proportional counter, where there is a coincidence between both PMT's and the PCS⁸. This is done by first setting up the coincidence between both PMT's. The PMT pulse after it is amplified by a timing filter amplifier is sent to a discriminator. The discriminator level is set at the 0.25 single photoelectron peak, to ensure that all photons are counted. The discriminator pulse width is varied for both PMT's, so that the coincidence window is less than 30 ns. A coincidence curve is shown in Figure 3.13 for the 2PMT's⁹. It is clear from the curve, and by studying both PMT pulses on an oscilloscope, that when we impose a 16 ns delay, we are in the middle of the counting plateau, and that the highest coincidence rate is observed. Next, it is necessary to set up a coincidence between the PMT's and the LLD of the proportional counter. This is easy, because the PMT's always occur before the full β pulse has developed in the proportional counter. Thus the 2PMT coincidence unit (C-PMT+PMT) response is sent into one input of a coincidence unit. The LLD pulse with a width of about 100 ns is sent to the other input of the same coincidence module. Thus, the coincidence unit (C-2PMT+PCS) will only respond when there is a triple coincidence of both PMT's with the PCS.

At this point the two event decision making techniques differ in how the PCS+2PMT events are classified. In the case of the CDM technique the oscilloscope is triggered on the NIM pulse out of the triple coincidence unit (C-2PMT+PCS), and each PCS+2PMT event is recorded and classified using the analysis program CDManalysis.f. This is the extent of the dependence of the CDM technique on the electronics utilized in the experiment. Consequently, the only relevant systematic uncertainty

⁸Late in this investigation, one of the PMT's became dis-functional, this does not change the logic much, since the two PMT coincidence gate (C-PMT+PMT) is just switched to an OR gate, and the dis-functional PMT is turned off.

⁹A coincidence curve is generated when one of the PMT's discriminator pulse is delayed with respect to the other PMT discriminator pulse, and for various values of the delay, the rate of PMT+PMT coincidences are recorded

Figure 3.13: A coincidence curve for the 2PMT coincidence.

in relation to the electronics is that the 2PMT+PCS coincidence is set correctly, and whether the LLD is set low enough, so that low amplitude events are not missed. However, in the EDM technique, the electronics involved are more complicated. To decide which type of event has occurred the output from the Just- α and DC, coincidence units (The coincidence units, described in the previous sections, that determine which event has occurred.) are sent into one of the inputs of two coincidence units (C'-JB2, C'-DC'2) where the other inputs of the modules are the 100 ns pulse telling whether a 2PMT+PCS coincidence has occurred. The response will be to classify which event has occurred in coincidence with both PMT's.

To record the PMT spectrum for each event type, it is necessary to delay the PMT pulse several μ s (10^{-6} s), because the decision of event type is made at least

2 μ s after the β has been observed in the PCS. This is performed by sending the PMT pulse after the timing filter amplifier into another amplifier (Ortec 440-A), and using the delayed output from this module into the peak sensitive V-mode of the QVT multi-channel analyzer. The NIM pulse used as a gate into the QVT (The gate that specifies the time during which the maximum height of the pulse is digitized), is the response out of the coincidence that reveals what type of triple coincidence event has occurred (either C-DC2 or C-JB2). In this way, only the spectra are taken for each classification of events.

The rates of all the various event classifications are measured, by connecting to each deciding coincidence module (CJA1,CJB1,..) a CAMAC controlled scaler. The reason this approach has been taken as opposed to the much simpler solution of just connecting a NIM scaler to the coincidence units, is because of low energy transient noise, which is at times evident in the PCS. It is observed that sometimes (usually at night) the LLD rate increases by several orders of magnitude. To prevent this noise from interfering with the various rate measurements, a FORTRAN program has been written that can read the scalers as a function of time. For example, if all the scalers are read simultaneously every 10 seconds for a run of several days, then the resulting Gaussian distribution of the rate measurements can be plotted. A cut can then be imposed on the noise events, since these manifest themselves as a pile-up of measurements in the high event rate tail of the Gaussian distribution. In this way the noise does not interfere with the rate measurements (this is shown in Figure 3.14 where the LLD rate is plotted for 5400, 10 s measurements).

In the case of the CDM technique, the rate measurements can be done using two methods, which have both given identical results. One method is to set the LLD to the same setting as the trigger on the oscilloscope, and then by utilizing the method above, the LLD and PCS+2PMT scalers can be read as a function of time. The second method is to start a timer and measure the number of acquisitions the oscilloscope has observed in this time.

Figure 3.14: This is the distribution of the LLD rate for 5400, 10 s measurements. The noise in the high rate tail of the Gaussian distribution is evident in the graph.

For the case where the event rates are determined without the 2PMT coincidence the trigger rate is too fast to record every event, since it takes some time for the oscilloscope to write all the data to a file. Thus the oscilloscope in this mode has a dead time of approximately 2 s. Consequently, to do accurate rate measurements it is necessary to determine the number of triggers within a certain time in normal mode, so that the oscilloscope traces are not recorded. Then, by taking the ratio of various event types with the LLD rate as determined by the program CDManalysis.f, the rate of the event classifications can be determined. The same method can be applied to the 2PMT coincidence rates, however, there is no dead time correction associated with the oscilloscope, since the PCS+2PMT rate is so low. In this way, the rates can be determined simultaneously when the oscilloscope traces are recorded.

3.6 Spectral Analysis

3.6.1 EDM Spectral Analysis

As Table 3.1 shows, all the different types of events with, and without the PMT coincidence assess different isotopes of the ^{232}Th chain. If the proportional counter spectrum is observed for the Just- α events, then the spectrum shows the energy distribution of the α 's for the 4 isotopes in the ^{232}Th chain below ^{228}Th , and the α due to the 36% branch of the decay of ^{212}Bi . Since the α 's saturate the pre-amp connected to the PCS, all that is seen is the exponential increase to the limit of saturation (see Figure 3.15). Also shown in Figure 3.15 are the β 's which are clearly visible in the lower part of the spectrum.

Figure 3.15: Pulse height spectrum showing the α saturating the electronics and the β 's decreasing toward higher pulse amplitude

The Just β events as viewed by the PCS, are sensitive to the 36% branch of ^{212}Bi , and to the β that is released in the decay of ^{212}Pb to ^{212}Bi . By demanding a coincidence of the Just- β events, and the 2PMT+PCS events, the spec-

tra as viewed by the PMT's, is sensitive mostly to the β that is released during the 36% branch decay of ^{212}Bi . This is because almost all the β 's that are released in the decay of ^{212}Pb to ^{212}Bi are below Čerenkov threshold for both the acrylic Čerenkov source and light water. Although only one isotope is selected, it is the least accurate because of the reasons mentioned in the previous sections. A spectrum for 12 days is shown in Figure 3.16 for the top PMT demanding a 2PMT+PCS+Just- β coincidence.

Next, the spectrum of the PMT's can be determined for the DC events. (shown in Figure 3.18). This should correspond to the β released for the 64% ^{212}Bi decay. Both these spectra are calibrated by fitting the single photoelectron peak at a higher gain to a gaussian. Then, by determining the mean of the fitted peak, and by extrapolating towards lower gains (where the above spectra were taken), the channel that the single photoelectron peak corresponds to can be found (the fit to a Gaussian is shown in Figure 3.17 for the spectrum shown in Figure 3.18).

Figure 3.16: Pulse height spectrum of the 2PMT+PCS+Just- β events as seen by the top PMT. Full scale corresponds to 5 photons.

Figure 3.17: Pulse height spectrum showing the Gaussian fit to the single photo-electron peak for the top PMT.

Figure 3.18: Pulse height spectrum of the 2PMT+PCS+DC' events as seen by the top PMT. Full scale corresponds to 5 photons.

Figure 3.19: Time spectrum showing the decay of the ^{212}Po state. The fitted curve corresponds to a half-life of 296 ± 2 ns.

A time spectrum can be determined (see Figure 3.19 where the LLD is the start, and the ULD the stop pulse into the T-Mode of the QVT), which shows the ^{212}Po state decaying with a half life of 300 ns. The fact that the χ^2 of an exponential fit to the data is close to 1, emphasizes that the electronics is preserving the timing of the decay of the ^{212}Po state with a high degree of accuracy, and that the ULD has been set high enough, so that only the α 's trigger the coincidence. The value experimentally obtained for the half life of the ^{212}Po state by fitting the experimental data to an exponential, was found to be 296 ± 2 ns (Error quoted is as reported by the fit), compared to an accepted value of 302 ± 3 ns (average taken from values found in [29]).

Figure 3.20: Pulse height spectrum of the β 's and α 's as observed in the PCS, as calculated using the CDM technique.

3.6.2 CDM Spectral Analysis

In the program CDMAnalys.f the pulse height of the first peak is determined for every event, and in the case of DC events, the pulse height of the second peak is also calculated. See Figure 3.20 for pulse height spectrum for both peaks. It is seen here (as is observed in Figure 3.15) that the β 's appear in the PCS as an exponential decay towards higher amplitudes, and the α 's saturate the pre-amp at about 3.5 V. This figure should be directly compared to Figure 3.15 where the EDM technique is utilized¹⁰. The CDM technique is more flexible than the EDM technique, in that much more can be learned from a single data set. For example, suppose it is of interest to determine the pulse height spectrum of the β and α separately. In the case of the EDM technique, it would require additional changes to the electronics, and it may also require (due to lack of equipment) for two separate data sets to

¹⁰A note of caution, these figures were taken at different voltages applied to the anode of the PCS. Upon comparison the superiority of the CDM technique is evident, in that Figure 3.15 shows distortion in the spectrum due to the electronics

be taken: one for the determination of the β pulse height spectrum, and one for the measurement of the α amplitudes. However, if the CDM technique is used, one data set needs only be taken to obtain both the Just- β and Just- α spectra, since all the pulse height information of one data set is preserved using this method. See Figure 3.21 and Figure 3.22 for the β and α pulse height spectrum as observed in the PCS.

Figure 3.21: Pulse height spectrum showing the Just- β selected events using the CDM technique.

In the analysis program, CDManalysis.f, the ULD is artificially set at 0.5 V, just as is done in the EDM technique. This is evident in the aforementioned figures, since there are no Just- α 's histogrammed below 0.5 V, and no Just- β 's histogrammed above 0.5 V. As was mentioned before, the only difference in how the events are classified with the CDM technique, is that the pulse height of the second pulse does not need to be greater than the ULD setting. See Figure 3.23 for the α pulse height spectrum of the DC classified events.

To determine the pulse height spectrum of one of the PMT's is more complicated, because the event is classified after the event has occurred. Thus, it is not classified on an event-by-event basis as is done in the EDM technique.

Figure 3.22: Pulse height spectrum showing the Just- α selected events using the CDM technique.

Figure 3.23: Pulse height spectrum of the α 's in the DC classified events using the CDM technique.

This means that to measure a pulse height amplitude for the PCS+2PMT+DC events (see Figure 3.18 and Figure 3.16 for the EDM analogues) and the PCS+2PMT+Just- β events, the relative order of appearance of the 2PMT+PCS signal must be recorded, so that after the data set has been classified, the events observed in the PMT's can be associated with the corresponding events observed in the PCS. This requires that when a 2PMT+PCS event occurs, both the signal observed in the PCS, and the signal in one of the PMT's needs to be recorded simultaneously. This has not been tested, but except for a requirement of more electronics, should not pose any problems.

3.7 Rate Analysis

The analysis described here is calculated using the FORTRAN program GORECKL.f included in the Appendix to this report. The program compares a χ^2 fit of the experimental data for each of the various event classifications, to what is expected from the theoretical estimates. The program utilizes the function minimization package MINUIT found in CERNLIB, to find the global minimum of the χ^2 function. The free parameters in the analysis described in the next section are the geometric efficiency¹¹ for the DC and Just- β PMT coincidences, the activity of the source, and two additional parameters f_{aja} and x , to be described in the next sections. The errors in the measurements that the fit assumes are statistical. However, calculated errors of various quantities appearing in the equations, and how they effect the fit, will be discussed later in this report.

3.7.1 Assumptions in the Fits

In a naive first study, various assumptions have been made in the calculations of the rates expected in the PCS, as compared to the experimental rates observed.

¹¹The term geometric efficiency refers to the ratio of β events that trigger a PMT coincidence to the number of β events that occur above the Čerenkov threshold.

- 1) The source, deposited on the wire, stays on the wire
- 2) There are no α 's below the ULD
- 3) There are no β 's above the ULD
- 4) There are no β 's below the LLD

These were assumed initially and gave a very bad fit of the experimental data to the theoretical expectations. Rather than explain in detail these equations which were based on a model which was too simplistic, the results obtained are stated but the details of the equations are not reported. With assumptions 1)-4) the χ^2 fit was found to be 28 per degree of freedom, and the activity of the source was extracted to be 20% lower than the best fit to be described later. With only assumption 1), the χ^2 decreases to 12 per degree of freedom, and the extracted activity remains 20 % lower than the most realistic model to be described below. In the equations that describe the rates of the various event classifications, several quantities appear, and must be calculated, such as the fraction of the β spectra seen in the PMT's, and the effect of the thickness of the wire on the rates observed. Other effects can not be calculated easily, and must be free parameters in the fit. Each is discussed separately below.

3.7.2 Effects Which Can Be Calculated

The Fraction of the β Spectrum Seen By the PMT's

Since, the PMT's are only sensitive to the β spectrum from the Čerenkov threshold to the endpoint, the PMT's only observe a fraction of the β spectrum. This fraction is determined by simulating the β spectrum using the SNOMAN¹² version 2.05 code for generating the β spectra. Ten thousand events were simulated, and the number of events that have β energies above the Čerenkov threshold were recorded. Thus, the fraction sought is the number of events above the Čerenkov threshold, divided

¹²SNOMAN is the main Monte Carlo, that simulates the geometry of the SNO detector.

by the number of events simulated. The reason for using the SNOMAN code is the ease at which the various branches for the β spectrum can be taken into account. In the analysis program f_2 is the fraction of events in the 64% ^{212}Bi branch, with a β energy above the Čerenkov threshold. Also, in the program, f_4 is the similar fraction for the ^{212}Pb β and the ^{208}Tl branch. The various branches for all the decays, are obtained from the Table of Isotopes[29]. No attempt has been made at rigorously calculating the energy for these particles as is done in the latest version of SNOMAN 2.08. Comparisons were made between SNOMAN 2.05 approximation to the β spectrum, and the shape of the theoretical spectrum¹³. These were found to be in acceptable agreement for this study.

The Effect of the Anode Wire

It is necessary to calculate the number of α 's that have a range comparable to the thickness of the wire (25 micron diameter), so that these will be absorbed by the stainless steel wire, and thus will not be detected in the proportional counter. If, for example, a number of the α 's in DC events are not detected, they will be classified as a Just- β event. Also, there will be a decrease in the number of Just- α events that are expected.

A FORTRAN program (WIRE.f) was written to calculate what the effect is of the wire on the α rate. This was done by simulating a point α source on the periphery of a stainless steel wire¹⁴. The program selects an α range for a particular α energy from a Gaussian distribution with a mean given by the mean ion depth, and a width given by the longitudinal straggling parameter described in [31]¹⁵. Then, a random direction (θ and ϕ) and radius given by the range is generated, simulating the isotropic emission of α 's from a source on the wire. Next, the program checks

¹³The theoretical spectrum used to compare the shape, was that found in [30]. The formula used was corrected for relativistic and screening effects.

¹⁴304 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).

¹⁵The 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.

whether the simulated α is in the wire or not. If it is in the wire, this corresponds to an event where the α 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. It must be mentioned that this fraction will vary with event classification, because each type of event is sensitive to α 's with different energies, and thus ranges. In the analysis program GORECKI.f, $f7$ is the correction of the DC events lost to the wire and ($f32, f14, f17, f18, f16$) are similar corrections for the Just- α event classification. These are the fractions of events simulated for each event classification that survive the wire. The errors expected for these calculations are due to the approximation of steel to iron in the straggling parameter.

3.7.3 Effects Which are Difficult to Calculate

The Effect of Nuclear Recoil

The main assumption that the ^{228}Th source deposited on the anode wire, is actually decaying on the wire, is incorrect. The ^{228}Th source proceeds through a series of α decays, and with each α decay, there is a certain probability (x in the fit program GORECKI.f) that the nuclear recoil of the daughter will be propelled from the wire into the active volume of the gas. We assume in the current analysis that α decay recoil will transport the daughter out of the wire, because on average 2% of the decay kinetic energy is given to the daughter nucleus. Thus, since all α 's in the ^{228}Th decay chain have an energy exceeding 5 MeV, the nucleus will have at least 100 keV, which is sufficient to overcome the chemical forces keeping the nuclei at the wire¹⁶. The daughter nuclei may be charged, because as the α travels through the electron cloud of the daughter nuclei, it can ionize the atom, and produce a positively charged daughter. If this is the case the daughter will drift in the electric field toward the walls of the PCS, where the daughter will continue through the

¹⁶It is assumed that if the source proceeds through β decay that the daughter nuclei will not have enough nuclear recoil to push the daughter out of the wire

series decay. Another possibility is that the daughter is not left in an ionic state, but that it will still diffuse towards the walls of the PCS. Once the daughter is at the walls, it will remain attached because of surface forces. In either case however, some part of the decay will occur at the walls, not on the anode wire. When a β or α decays at the wall, the probability of the particle travelling into the active volume of the detector (f_{wall} in the fit program GORECKI.f) is $1/2$, a purely solid angle argument. Furthermore, (neglecting spatial inconsistencies in the electric fields in the PCS) we expect the source density of the daughter products on the wall to be very small, so that we do not expect f_{wall} to deviate much from $1/2$ because of α self-absorption. The effects to correct for in the rate equations are that:

- There is x probability that an α decay produces a daughter that will travel to the walls of the PCS.
- Once the daughter is at the walls it will stay there.
- When an isotope decays at the walls, the α or β associated with that decay will have a $1/2$ probability of going into the active volume of the PCS.

It is easy to take into account this effect into the rate equations for each event classification, because we can separate the equations for each event type by the amount decaying at the wire, and the amount we expect to be decaying at the wall. Let us proceed by following the series decay from ^{228}Th to ^{220}Rn , and determining the fractions left of the various isotopes at the wire and on the walls. First, when ^{228}Th decays by producing an α and ^{224}Ra , a fraction x of the ^{224}Ra will end up on the wall, and a fraction $(1 - x)$ will be left on the wire. When the ^{224}Ra decays to ^{220}Rn by α decay, we have a f_{wall} (set at $1/2$ in the program) chance of detecting it at the walls, and a f_{14} chance of (corresponding to the wire correction discussed earlier for the ^{224}Ra) detecting the α at the wire. Consequently, the total fraction detected in the PCS for the ^{224}Ra α is:

$$\begin{aligned} \text{Fraction of } \alpha \text{'s detected} &= (\text{detection efficiency at wire}) \cdot (\text{amount at wire}) \\ &\quad + (\text{detection efficiency at walls}) \cdot (\text{amount at walls}) \end{aligned}$$

$$\text{Fraction of } \alpha \text{'s detected} = f_{14} \cdot (1 - x) + (1/2) \cdot x$$

When the ^{220}Rn decays again to ^{216}Po , then the amount $(1 - x)$ of ^{216}Po on the wire, will decrease once more by the factor $(1 - x)$, and the fraction traveling to the walls will be $x(1 - x)$. As a result the amount of ^{216}Po present at the walls is $x + x(1 - x)$. It becomes clear that we can represent the fraction of the various isotopes present at the walls by the following formula:

$$\begin{aligned} \text{Probability that the daughter of the } n\text{'th } \alpha \text{ decay is on the wall} &= \sum_{i=0}^{n-1} (1 - x)^i \cdot x \\ \text{Probability that the daughter of the } n\text{'th } \alpha \text{ decay is on the wire} &= (1 - x)^n \end{aligned}$$

These formulae can be readily applied to the theoretical equations describing the rates, by adding up the contributions from each isotope that are part of each event classification. See the program GORECK1.f for the fraction at the wire, and on the walls, for each event classification.

Fraction of α Spectrum Above ULD

The assumption that all the α 's are above the ULD needs to be relaxed, since it is likely that some of the α 's are losing so much energy as they travel through the wire, or that the solid angle is such that many of the α 's do not deposit enough energy to produce a pulse amplitude exceeding the ULD. As a result, these events will appear as a β . Hints of this effect are in the DC' rate measurements, shown in Figure 3.24 where it is seen that there is an upward slope in the DC' count rate, as the ULD is set to lower levels. The only event that can give a delayed second pulse longer than 300 ns is the α corresponding to the DC' events, as such we have a sense of what the α amplitudes are like for α 's in the PCS. One would

have expected that there is a point where the ULD is set to such a low level, that every α is above the ULD, so that the DC rate remains constant. However, this is not evident in Figure 3.24 where there seems to be a downward trend towards higher ULD settings, indicating that the α spectrum is being cut-off as the ULD is increased. We expect the fraction of the α spectrum above the ULD to be lower

Figure 3.24: DC selected rates plotted against the ULD setting. The EDM technique is utilized to obtain this graph.

for Just- α events, because the energy of the α is at least 30% lower than the α 's in the DC classification. Thus we assume in the fits that the fraction of the DC α 's above the ULD (f_{adc}) is 1.0¹⁷. The variable f_{aja} is the fraction of the α spectrum for the Just- α events above the ULD, it is a free parameter in the χ^2 fit described below.

¹⁷If the value of f_{adc} is changed by as much as 20%, the χ^2 fit still extracts an activity within a 2% of the best fit value. Thus, varying f_{adc} does not seem to matter much according to the fit.

3.7.4 The Equations Used in The Analysis of the Rates:

The equations that are used in the χ^2 fit in determining the rates for the various event classifications are summarized below, along with an explanation of what each term physically corresponds to. The notation in this section is at best cumbersome; this is so that there is no confusion with the notation used in the program. Please refer to Appendix A for definitions of the symbols used in the equations below.

Just- β Rate:

$$\begin{aligned}
 R_{\beta} = & \underbrace{(jbwa \cdot fwall + jbw i) \cdot (fljb - fhjb) \cdot Act}_{1a} \\
 & + \underbrace{(jawa \cdot fwall + jawi_wire) \cdot (1 - faja) \cdot Act}_{1b} \\
 & + \underbrace{f5 \cdot dcwi \cdot (1 - f7 + f6 + (1 - fadc)) \cdot (fldc - fhdc) \cdot Act}_{1c} \\
 & + \underbrace{f5 \cdot dcwa \cdot (1 - fwall + f6 + (1 - fadc)) \cdot (fldc - fhdc) \cdot Act}_{1ccont.} \\
 & + \underbrace{f13 \cdot f22 \cdot (1 - fwall) \cdot x \cdot x2s \cdot Act}_{1d} \\
 & + \underbrace{(1 - f5) \cdot f15 \cdot f21 \cdot (1 - fwall) \cdot x \cdot x4s \cdot Act}_{1dcont.} \\
 & + \underbrace{f11 \cdot f20 \cdot (1 - f32) \cdot Act + (1 - x) \cdot f13 \cdot f22 \cdot (1 - f14) \cdot Act}_{1e} \\
 & + \underbrace{(1 - f5) \cdot f15 \cdot f21 \cdot (1 - f16) \cdot (1 - x)^4 \cdot Act}_{1econt.} + \underbrace{bbg}_{1f}
 \end{aligned}$$

- 1a) $\rightarrow$ This is the sum of the β rate expected from the ^{208}Tl decay, and the β that is expected from the decay of ^{212}Pb to ^{212}Bi (true Just- β events).
- 1b) $\rightarrow$ This is the β rate expected from the true Just- α 18 events that have the α below the ULD.
- 1c) $\rightarrow$ These are the 64% ^{212}Bi events when the α is not detected due to:

¹⁸True Just- α events correspond to the α 's from the decays of ^{228}Th , ^{224}Ra , ^{220}Rn , ^{216}Po , and the 36% decay of ^{212}Bi .

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1. The case where the β and α are separated with a time greater than t_m , so that the ULD does not fire within the long gate (t_m) triggered by the LLD.
 2. The fraction of events where the α is either absorbed in the wire, or in the case of nuclei decaying on the walls, it is the fraction of events where the α gets absorbed in the walls of the PCS.
 3. The fraction of DC events where the α pulse amplitude is less than the ULD.
- 1d),1e) $\rightarrow$ This is the β rate expected when two requirements are met:
 1. A ^{232}Th chain isotope proceeds by α decay to an excited state (instead of the ground state) which decays by releasing an electron which is detected by the PCS.
 2. The α that is released, is absorbed in the stainless steel anode wire, or the walls of the PCS.
 - 1f) $\rightarrow$ This is the experimentally measured Just- β background

DC Rate:

$$R_{DC} = f5 \cdot (dcwa \cdot fwall^2 + dcwi \cdot f7) \cdot (f1 - f6) \cdot fldc \cdot Act + dcby$$

- This is the DC rate due to the decay of ^{212}Bi to ^{212}Po that is expected. This equation takes into account the α detection efficiencies, and the requirement that the separation time, t_s of the β and the α must satisfy $\tau_{cut} < t_s < t_m$

Just- α Rate:

$$\begin{aligned}
 R_{\text{Just-}\alpha} = & \underbrace{j_{awa} \cdot f_{wall} + j_{awi_wire}}_{3a} \cdot f_{aja} \cdot Act \\
 & + \underbrace{j_{bwa} \cdot f_{wall} + j_{bwi}}_{3b} \cdot f_{hjb} \cdot Act \\
 & + f_5 \cdot \underbrace{(dcwi \cdot f_7 + dcwa \cdot f_{wall})}_{3c} \cdot \underbrace{((1 - f_1) \cdot fhdc + (1 - f_1) \cdot fadc - (1 - f_1) \cdot fhuc \cdot fadc)}_{3c \text{ cont.}} \cdot Act \\
 & + f_5 \cdot \underbrace{(dcwa \cdot f_{wall} + dcwi \cdot f_7)}_{3d} \cdot fadc \cdot \underbrace{(f_1 - f_6) \cdot (1 - fldc)}_{3d \text{ cont.}} \cdot Act + \underbrace{abg}_{3e}
 \end{aligned}$$

- 3a) $\rightarrow$ These are the true Just- α events where the α is above the ULD
- 3b) $\rightarrow$ These are the true Just- β events where the β has an amplitude exceeding that of the ULD.
- 3c) $\rightarrow$ These are the 64% ^{212}Bi events where the separation time t_s satisfies $t_s < \tau_{cut}$ and either the α or β amplitude exceeds the ULD.
- 3d) $\rightarrow$ These are the 64% ^{212}Bi events where the β is not detected, since the β amplitude is less than the ULD, but the α has an amplitude exceeding the ULD.
- 3e) $\rightarrow$ This is the experimentally measured Just- α background when the ^{228}Th source is not present in the PCS.

PCS · PMT · Just- α Rate:

$$\begin{aligned}
 R_{PCS \cdot PMT \cdot Just-\alpha} = & \underbrace{f4 \cdot (jbwi + jbwa) \cdot fhjb \cdot Eff_{-jb} \cdot Act}_{4a} \\
 & + \underbrace{f2 \cdot f5 \cdot dcwi \cdot ((1 - f1) \cdot fhdc + (1 - f1) \cdot fadc \cdot f7)}_{4b} \\
 & - \underbrace{(1 - f1) \cdot fhdc \cdot fadc \cdot f7 \cdot Eff_{-dc} \cdot Act}_{4b \text{ cont.}} \\
 & + \underbrace{f2 \cdot f5 \cdot dcwa \cdot ((1 - f1) \cdot fhdc + (1 - f1) \cdot fadc \cdot fwall)}_{4c} \\
 & - \underbrace{(1 - f1) \cdot fhdc \cdot fadc \cdot fwall \cdot Eff_{-dc} \cdot Act}_{4c \text{ cont.}}
 \end{aligned}$$

- 4a) $\rightarrow$ These are the true Just- β events, where the β has an amplitude exceeding the ULD.
- 4b) $\rightarrow$ These are the 64% ^{212}Bi events for the source present at the wire, when the separation between the β and α satisfies $t_s < \tau_{cut}$, and the amplitude of either the α or β is above the ULD threshold.
- 4c) $\rightarrow$ This is the same as the above term 4b), except that this is for the events decaying on the wire.

PCS · PMT · Just- β Rate

$$\begin{aligned}
 R_{PCS \cdot PMT \cdot Just-\beta} = & \underbrace{f4 \cdot (jbwi + jbwa) \cdot (fljb - fhjb) \cdot Eff_{-jb} \cdot Act}_{5a} \\
 & + \underbrace{f2 \cdot f5 \cdot (dcwi + dcwa) \cdot (f6 + (1 - fadc)) \cdot (fldc - fhdc)}_{5b} \\
 & \cdot \underbrace{Eff_{-dc} \cdot Act}_{5b \text{ cont.}} \\
 & + \underbrace{f2 \cdot f5 \cdot (dcwi \cdot (1 - f7) + dcwa \cdot (1 - fwall)) \cdot (fldc - fhdc)}_{5c} \\
 & \cdot \underbrace{Eff_{-dc} \cdot Act}_{5c \text{ cont.}} \\
 & + \underbrace{cjbhg}_{5d}
 \end{aligned}$$

- 5a) $\rightarrow$ This term is the rate expected from the true Just- β events.
- 5b) $\rightarrow$ These are the 64% ^{212}Bi events where the β and α is separated with a time greater than t_m , and the events where the α is below the ULD.
- 5c) $\rightarrow$ These are 64% ^{212}Bi events where the α is absorbed either in the walls of the PCS or the wire.

PCS $\cdot$ PMT $\cdot$ DC Rate:

$$R_{PCS:PMT:DC} = f5 \cdot (dcwa \cdot fwall + dcwi \cdot f7) \cdot (f1 - f6) \cdot (fldc + fadc - fadc \cdot fldc) \cdot Eff_{dc} \cdot Act$$

- This is the rate determined purely from the 64% ^{212}Bi events with a β above the Čerenkov threshold. In several days of counting there has been no background detected to this measurement.

LLD Rate:

$$R_{LLD} = R_{\text{Just-}\beta} + R_{\text{Just-}\alpha} + R_{DC}$$

- This is the total LLD firing rate expected.

3.7.5 Results of the Fit

A χ^2 fit was performed on the experimental rates for the various event classifications, determined using the CDM technique¹⁹. The fit used the equations described in the previous section, with the activity, the geometric efficiencies (Eff_{dc} and Eff_{jb}), the variable x and $faja$ free parameters. The results of the fit with these 5 free parameters gave a χ^2 per degree of freedom of 1.045. See Table 3.2 for the experimental data and the fitted results for the various event classifications.

¹⁹The results here are presented for a 1PMT+PCS coincidence, and using CDM classified events.

Event Type Rates	Experimental Value (Hz)	Fitted Value(Hz)
$R_{Just-\beta}$	0.9728 ± 0.0292	0.9728
R_{DC}	$5.102E-2 \pm 0.0071$	5.1052E-2
$R_{Just-\alpha}$	1.0811 ± 0.0324	1.0811
$R_{PCS-PMT-Just-\alpha}$	$1.0521E-3 \pm 1.578E-4$	8.7886E-4
$R_{PCS-PMT-Just-\beta}$	$2.2196E-2 \pm 6.659E-4$	2.2195E-2
$R_{PCS-PMT-DC}$	$7.5156E-4 \pm 1.353E-4$	8.7884E-4
R_{LLD}	2.105 ± 0.0463	2.1050

Table 3.2: The experimental and fit values for the rates of various event classifications. The CDM technique was utilized and one PMT was dis-functional.

The activity extracted in the fit program GORECKL.f was found to be, $Act_{best} = 0.50 \pm 0.028$ Hz. The error on the activity was found by adding in quadrature:

1. The error reported in the value of the extracted activity reported by MINUIT.
2. The spread in extracted activities, when various parameters in the program were changed from their assumed value by 5%-20%. This was done for 35 different fits, where each fit corresponds to a particular deviation of a parameter from their expected value. For example, the variable *fadc* was varied by 10% and this did not significantly effect the activity. It has not been possible to vary all the parameters in the program randomly and simultaneously. So to take this into account, the error added in quadrature is the difference in the highest and lowest extracted activity, and not the deviation of the activity from the best fit value, Act_{best} .

Since the set of equations is in principle an over-determined system (since there are 7 equations ²⁰and 5 unknowns, see the previous section) we can do a consistency check on the fitted results, by eliminating various equations, and checking how well the extracted activity compares to the value above. For example, when we eliminate the last equation (R_{LLD}) the value for the χ^2 per degree of freedom, and

²⁰All of the equations are independent except for the LLD rate which is dependent on the Just- β , Just- α , and DC rates.

the extracted activity remain essentially the same. This is not surprising, since the equation eliminated, is the sum of the first three equations, and if the event classification program is working properly, all events should be accounted for. As a result, this equation gives no extra information. A more interesting situation arises if the delayed coincidence equation is eliminated, which is the best measurement we can make (R_{DC} has no backgrounds associated with it). Here we see that the extracted activity is found to be 0.43 ± 0.07 Hz, which is still consistent with the value obtained if the DC measurement is included. A summary of the values of the free parameters obtained is shown in Table 3.3.

Free Parameter	Extracted Value	Uncertainty
<i>Act</i>	0.50 Hz	0.19E-01 Hz
<i>Eff_dc</i>	0.12E-01	0.14E-02
<i>Eff_jb</i>	0.93E-01	0.57E-02
<i>faja</i>	0.80	0.18E-01
<i>x</i>	0.40	0.13

Table 3.3: The extracted values for the fit of CDM classified experimental data to the theoretical rate equations.

3.7.6 Comparison of Extracted to Expected Results

The Geometric Efficiency and Activity The geometric efficiency is discussed at length below and the activity only briefly, because the validity of the geometric efficiency extracted can be verified by Monte Carlo (CERCELL.f) but the activity can only be verified by independent experiment. However, since the activity was found to be relatively stable when certain parameters are varied, and equations eliminated, it allows us to be confident of the extracted value.

The viability of the geometric efficiency can be determined by Monte Carlo, that is, by simulating the Čerenkov Cell geometry. This has been done in the program CERCELL.f with several assumptions in the generation of the β Čerenkov photons and the Čerenkov Cell geometry. (see Figure 3.25 for the geometry assumed in the

Figure 3.25: The geometry simulated in CERCELL.f Monte Carlo.

Monte Carlo.) The program first generates a β energy and direction. Next, the program calculates the number of photons detected by the PMT's by including the quantum efficiency of the SNO PMT's, and integrating the full response function from 320 to 520 nm²¹. In this way, the program does not have to generate the energy of each Čerenkov photon, since it is already taken into account in the integral of the response function. Thus, not all the Čerenkov photons have to be followed in their propagation through the Čerenkov Cell, rather only the amount expected to arrive at the PMT's need to be simulated. After the number of PMT hits has been decided,

²¹For a detailed explanation of this calculation refer to SNO Technical Report STR-94-050, C.K.Hargrove and E. Dalnoki-Veress, An Analytic Calculation of the Number of PMT Hits for Monoenergetic Electrons Borne at the Centre of the SNO Active Volume.

it is necessary to determine how many of these will be reflected by the aluminum layer on the inside of the Čerenkov Cell, lose their intensity, and ultimately not be detected. This is done by generating the Čerenkov photons on a 48 degree cone, corresponding to the Čerenkov angle of acrylic (the current Čerenkov source as has been mentioned is an acrylic cylinder surrounding the PCS, simulated in the program as an infinite acrylic medium). The program allows the photons to reflect from the aluminum cylinder walls and each time this happens, it loses its intensity given by the reflection coefficient. Thus, a photon generated may bounce 3 times, so that much of its initial intensity is lost²². The photon is followed toward the end of the cylinder, where the PMT is simulated as a flat disk. If the photon makes it to the PMT, and does not escape by propagating through the circular annulus or becomes absorbed in the cables (simulated as a 3 cm totally absorbing strip running vertically along the Čerenkov cell) surrounding the PMT, then its intensity is summed. The geometric efficiency is determined by calculating the number of events that have the number of fractional photons greater than 1 for a particular PMT, divided by the number of events simulated above the Čerenkov threshold²³. In this analysis, the reflectivity is assumed to be constant, and independent of the angle of incidence. This is an approximation because the reflectivity theoretically varies with the angle of incidence, and more importantly the reflectivity will be different along the wall of the cylinder. This is because there are many imperfections along the aluminum wall that change its reflective coefficient. Thus, the reflectivity can be seen as a free parameter in the program CERCCELL.f. Nevertheless, the results specify a reasonable range for the geometric efficiency. It is seen in Figure 3.26 that the efficiency of the geometry varies from 1% to 14% over the range of reflectivity 0.2

²²This is of course an approximation, because single photons are either absorbed or reflected, they do not lose energy in a continuous way. The program should be viewed as generating many photons with the same direction, so that the intensity of the beam is lost, because a certain amount of the original number of photons, is absorbed, not reflected.

²³Late in this investigation the base of one of the SNO PMT's became dis-functional, and so the coincidence rates assume a 1PMT+PCS coincidence not a 2PMT+PCS coincidence. If a 2PMT+PCS is simulated the efficiency decreases by at least a factor of 3 from the values quoted below

to 0.8. This is in reasonable agreement with the experimental value of $9.29 \pm 0.14\%$ obtained in the 5 parameter χ^2 fit described in the previous section.

Figure 3.26: Geometric Efficiency for PCS+PMT+Just- β events as calculated by the CERCELL Monte Carlo when the reflectivity is varied

When the ratio is taken of the simulated Just- β and DC geometric efficiencies (we thus have a parameter which is essentially independent of the geometry of the Čerenkov Cell) it does not compare well with the ratio of the geometric efficiencies in the fit. The fit extracts a ratio of the 0.13 ± 0.017 , and the Monte Carlo a value of 2.9. Perhaps an explanation for this anomaly is the fact that the background put into the fit, is the relative percentage background for the 2PMT+PCS+Just- β event classification. However, the fits are based on data with a one PMT coincidence, not a second PMT coincidence. As a result, the efficiency for seeing a coincidence is higher without the added constraint of demanding a 2PMT coincidence. Thus, if the background due to cosmic rays is high in the 1PMT+PCS coincidence rate, the fixed background measurement will not properly account for this increase in the rate. To compensate for this, the fit increases the value of Eff_{jb} without adjusting any of the other event classification rates. It must be mentioned that the

reason the 1PMT+PCS+DC' measurements are not affected by this, is because the DC' measurement has no background associated with it. We can make an estimate of this effect by taking the ratio of the rates measured with the 1PMT and 2PMT coincidences with the PCS.

$$\begin{aligned}
 R_{1PMT+PCS+JB} &= 0.022196 \pm 0.000745 \text{ Hz} \\
 R_{2PMT+PCS+JB} &= 0.008290 \pm 0.000172 \text{ Hz} \\
 \text{ratio} &= \frac{R_{1PMT+PCS+JB}}{R_{2PMT+PCS+JB}} \\
 &= 2.6774 \pm 0.10565
 \end{aligned}$$

Thus, the ratio established above is an estimate of how to correct the 1PMT coincidence rate for a measured 2PMT coincidence rate. In this way, we can adjust the measured 2PMT+PCS+Just- β background, by just multiplying the background by the factor determined above to obtain the 1PMT+PCS+Just- β background. When this background is put into the 5 parameter χ^2 fit mentioned earlier, the factor of 3 above only reduces the 1PMT+PCS+Just- β coincidence rate by $35\% \pm 4\%$, which is not enough to explain the discrepancy in the ratio of the geometric efficiencies. The reason for the inconsistency of the extracted geometric efficiency, and what is expected, will be studied further in the future.

3.8 Conclusions: Extrapolating the Experience to SNO

The previous discussions show that the experimentally obtained rates for the various event classifications compare well with the theoretical rates. The question of the accuracy of the activity extracted using the χ^2 fit needs to be addressed by an independent measurement, because one of the main advantages of the PCS is that it is assumed to be self-calibrating. This will need to be verified by independently measuring the activity on the wire in a separate detector. A value of $Act_{\text{wire}} =$

0.50 ± 0.028 Hz has been extracted from the χ^2 fit. It should be mentioned that the measurements obtained in this first stage of testing is the worst case scenario, because in the next stages of testing this technique, the backgrounds induced by cosmic rays will be vetoed, and various improvements in the designs of the PCS will be invoked. These improvements in the design will be discussed in the next chapter. In conclusion, in this first stage of testing the PCS has demonstrated it may be used as a low energy calibration source for SNO, assessing the shape and magnitude of the activity in SNO. The expectation is that if the spectral shape and amplitude is determined using the PCS, the background in SNO can be fit to the same shape, and by studying the amplitude, the activity due to isotopes in the lower half of the ^{232}Th chain can be determined.

Chapter 4

Thoughts for the Future

4.1 Making the PCS a Smaller Diameter

Experience with the proportional counter has shown that it would be advantageous to make the PCS a smaller diameter. The main reason for this is to improve the rise time of the α 's in the proportional counter, since the avalanche of electrons that is created due to the α is collected quicker at the anode. This is because the electric field inside the detector is inversely proportional to the radius of the cathode aluminum cylindrical sheath, and the time it takes to collect the signal (t), is proportional to the cathode radius (b) squared minus the anode radius (a) squared.

$$t \propto (b^2 - a^2)$$

The proportionality constant depends on such factors as the pressure inside the PCS and the mobility of the ion at the radius of the cathode. It is clear that if the cathode radius (b) is decreased, so will be the time to reach half the maximum pulse amplitude¹. If the rise time of the α in the PCS is faster, it will allow fewer DC events which have a β and α separated closely in time, to be classified

¹It should be mentioned that, care must be taken that the multiplication factor does not increase too much, so that non-linearities due to space-charge effects will become apparent

as Just- α events (since τ_{cut} can be set to a smaller value). This will improve the efficiency of the detection of the DC events. Also, if the cathode radius is decreased, it will proportionally lower the natural activity out of which the detector is constructed, and the background induced due to cosmic rays interacting at or near the PCS. It should be mentioned that a lower limit to decreasing the radius is where it becomes clear that β 's can not be distinguished above the electronic noise in the proportional counter. Thus the next major improvement to the prototype which has become apparent in the current study is that the cathode radius must be decreased.

4.2 Making the PCS Longer

It will be necessary in the next few years to do a full EGS4 simulation of the PCS geometry, and it will have to be linked to the SNOMAN code (The main SNO Monte Carlo). However, in the endcap region of the proportional counter, the β is complicated to simulate. Thus, an added simplicity in the EGS4 simulation of the proportional counter is to increase the length of the wire, and thus the cylinder (see Figure 4.1). In this way, the source is far from the endcap on both sides of the

Figure 4.1: Diagram of the PCS where the length of the cylinder is increased so that the number of events affected by the endcap is decreased.

detector, so that not many β 's will interact in the endcap region. EGS4 simulations were done, where the PCS was simulated as an Argon cylinder with a point ^{208}Tl

source. The percentage of the events lost due to the endcap region was calculated for various lengths of the proportional counter. This is shown in Figure 4.2 below.

Figure 4.2: Graph showing the percentage of the ^{208}Tl β 's that were affected for various lengths and radii of the PCS

It is clear that if the length of the cylinder is increased to 12 cm, a small fraction of the events interact with the endcap.

4.3 Amplitude Cuts to Reject β 's Travelling Toward Endcaps

It might be possible to reject β events that go toward the endcaps of the proportional counter by amplitude analysis. To understand this, it is only necessary to consider a β that travels at an angle ζ as is shown below in Figure 4.3.

Note: Track 3 inside the active volume is longer than track 1 (which has a larger value of angle ξ). So it is not strictly true that an amplitude cut corresponding to the distance of track 3 in the active volume corresponds only to events going toward the endcaps. Instead the amplitude cut must correspond to track 2 above, along the circle with a radius from the source to the endcaps.

Figure 4.3: Diagrams showing the possibility of applying cuts to the amplitude of the β . In part a) the distance from the source to the endcaps is much larger than the radius of the PCS and the high amplitude β events can be rejected with a high efficiency. In part b) it is emphasized that if the distance between the endcaps is small compared to the radius of the PCS then amplitude cuts will veto events which do not go toward the endcaps, such as β track 2 above. Thus it is important to ensure that the distance between the endcaps is large compared to the radius of the PCS.

This β will produce more electron-ion pairs because its track is longer, than if the β would have travelled along the radius of the proportional counter. This will increase the number of primary electrons that will create avalanches, so that the total charge collected is increased proportionally. A minimum ionizing β will create about 96 electron-ion pairs if the electron travels radially outward. Correspondingly, if a β travels at an angle ζ with respect to the radially outward direction, then the number of primary electron-ion pairs increases as the inverse of the cosine. Thus, it is clear that if β 's travel toward the endcaps, so that ζ is large the amplitude of the β pulse will be higher² In this way, by electronically rejecting high amplitude β 's, the events going toward the endcaps can be rejected. It should be mentioned, that there is an added advantage for doing a high amplitude rejection of events, since it may reject background from cosmic rays as well. This is because the PCS is oriented with its endcaps vertically with the ground. Since cosmic ray muons are favoured to travel vertically down, they will be more likely to travel the full distance of the PCS. Thus, there is a possibility that by employing these amplitude cuts, the background from cosmic rays may be decreased as well.

4.4 Independent PCS Testing

It is clear that to be certain that the PCS is self-calibrating, we need to determine the activity of the source on the wire independently, using a different detector. This needs to be done so that this activity can be compared to the activity extracted in the previous chapter using a χ^2 fit to all the data. To know the exact activity of the source deposited on the anode is crucial to the success of the PCS, because all the rate calculations depend on the activity of the source.

²There is a danger here, because if the distance to the thin acrylic endcaps (which define the active volume of the PCS) is small, compared to the radius of the detector, then β 's that have a very large ζ will travel a path much smaller than the oblique path defined by the distance from the source to a point along the circumference of the thin acrylic endcaps (see Figure 4.3).

4.5 Making the PCS Anode Wire a Smaller Diameter

The effect of the wire (as was discussed in the previous chapter) causes many of the α 's to be absorbed in the wire. This effect for the current radius anode wire (25 micron) is significant. The amount of α 's lost in the energy range 4-10 MeV, is 42%-15%. So that, if the radius is decreased, one expects the number of α 's to be absorbed in the wire to decrease as well. The effect of some possible anode wire diameters has been studied with the WIRE.f Monte Carlo discussed earlier. The results are shown below in Figure 4.4 for α 's of energy 4-10 MeV, for various wire diameters. In particular a 12.5 micron stainless steel wire is a possible candidate since it is readily available.

Figure 4.4: Fraction of the α 's absorbed as a function of the α energy for two different radii. From the graph it is clear that by going to smaller radii, fewer α 's are absorbed in the wire.

4.6 Investigation of the Three Particle Events

In the current study it was noticed that much of the time, when looking at delayed coincidence events, three pulses were seen in the detector (see Figure 4.5). Further,

Figure 4.5: Oscilloscope trace showing a three particle event

it was postulated that these extra pulses may be due to β particles. In this case, two pulses that are separated by a few hundred ns in time are observed, and if the second pulse is of a high enough amplitude, it can be classified as a DC event. This is important, because we then have a viable background to the event classification that we can measure with the highest accuracy. Furthermore, these events may occur with a PMT coincidence, so that these measurements will also have a background associated with them. In the early stages of this study, the electronics was set, so that the ULD would mis-classify these events as DC events. It was seen in these studies that there was some distortion in the delayed coincidence time spectrum,

that was not consistent with a decaying ^{212}Po state. Later, when the possibility of the presence of an extra pulse came to light, the ULD was raised much higher, so that it was just below the saturation point of the pre-amp. The result was a very clean exponential delayed coincidence time spectrum with a χ^2 fit close to 1. Furthermore, it was noticed by studying the DC rate, that this rate increased when τ_{cut} is decreased (see Figure 4.6 for this trend). With the CDM technique of

Figure 4.6: The DC classified event rate is shown as a function of τ_{cut} . Also shown is the theoretical DC rate normalized to the rate at 500 ns. The errors are assumed to be statistical for the experimental rates, and to be 20 ns for τ_{cut} . The errors in the theoretical rate are assumed to be the statistical error in the measurement at 500 ns added in quadrature with the 20 ns error in τ_{cut} .

classifying events this was studied further, since here we do not have the constraint that the second pulse in a DC event must have its amplitude exceeding that of the ULD. In this way, we can study the pulse height of the second pulses. A histogram of the second pulse amplitude is shown in Figure 4.7, where it is seen that there

are many low amplitude events comparable to the β amplitude. Furthermore, a

Figure 4.7: Histogram of the second pulse amplitude of a DC classified event using the CDM technique

scatter plot is shown in Figure 4.8, where the second pulse amplitude is plotted against t_s . Here, it is observed that 30% of all the DC events with $t_s < 400$ ns have an amplitude less than 1 V, and a separation time $t_s < 250$ ns. Thus, we can conclude that most of the low amplitude events also have a very short separation time between the first and second pulses.

It is uncertain what the reason is for these low amplitude, short separation time second pulses, in DC classified events. However, it is likely that these pulses are due to clusters of secondary electrons, that are formed around the primary electron tracks. For Argon, minimum ionizing particles are expected to produce on average 27 clusters per cm of track, 1.4% of which are expected to exceed 20 secondary electrons[32]. Thus, we have at least a 40% probability that a β produces a cluster

Figure 4.8: Scatter plot of the second pulse amplitude of a DC classified event plotted against the first and second pulse separation times τ_s , using the CDM technique

that exceeds 20 electrons³. If the cluster is produced at the end of its track, it will take up to 300 ns for the cluster of electrons to arrive at the anode (since the drift velocity for P10 is about 3 cm/ μ s, for a high reduced field [33]). In this case, we would have a 300 ns separation time, between the initial start of the β pulse, and the second pulse. However, as is shown in Figure 4.6, if a $\tau_{cut} = 300$ ns is imposed, the experimental rate will not be sensitive to the effect discussed, regardless of what the reason is for these second pulses. It should be mentioned, that this is another motive for making the next design of the PCS a smaller radius, since the drift time for electron clusters will be shorter, and thus smaller τ_{cut} 's may be imposed.

³Since a β will produce on average 80 primary electrons per track, the amplitude of this burst is greater than 1/3 of the initial β pulse.

4.7 Summary of Design Changes

As a consequence of this study, various design changes will have to be made to the PCS:

- The PCS will be made a smaller diameter.
- The stainless steel anode will be made a smaller diameter.
- The PCS will be made longer.

It will also be necessary to confine the source to the wire, so that the uncertainty in the calculations of the rates is minimized⁴. One possibility is to cover the anode wire with a thin gold layer by vacuum deposition, which will prevent the nuclei from leaving the wire, but still allow the α 's to enter the active volume.

4.8 Summary of Analysis Changes

The CDM method of classifying events has proven to be superior for many reasons:

- The method is less sensitive to various electronic uncertainties present when the EDM technique is utilized.
- The method will save time, since the electronics will only need to be set up once, for various sources.
- More can be learned from one data set than could be learned if the EDM technique is used. For example, if it is of interest to study DC rates as a function of τ_{cut} , all that is required, is to make minor adjustments to the analysis program. However, if the EDM technique would be utilized many changes would have to be made to the electronic set-up.

⁴It is assumed that α is the same for every isotope undergoing α decay. This assumption might not be correct.

- This method makes the PCS very portable, since not much electronics is necessary. This will be important in the next stage of testing at the University of Washington where a test version of SNO, is being set up.

Appendix A

Abbreviations

SNO Sudbury Neutrino Observatory

SSM Standard Solar Model

NSSM Non Standard Solar Model

BP Bahcall and Pinsonneault

TCL Turck-Chize and Lopes

SNP Solar Neutrino Problem

DFL Degl'Innocenti, Fiorentini, and Lissia

CC Charged Current reaction

NC Neutral Current reaction

ES Elastic Scattering reaction

CNO Carbon-Nitrogen-Oxygen

PCS Proportional Counter Source

PSUP Photomultiplier Support Structure

MSW Mikheyev-Smirnov-Wolvenstein

PMT Photomultiplier

EDM Electronic Decision Making

CDM Computational Decision Making

NIM Nuclear Instrumentation Modules

DC Delayed Coincidence

mwe meters water equivalent

ULD Upper Level Discriminator

LLD Lower Level Discriminator

Appendix B

Symbols and Definitions

Free Parameters in the Fit

Act = The activity of the ^{228}Th source

Eff_{dc} = The geometric efficiency for the DC events. This is defined as the fraction of events above the Čerenkov threshold that produce a PMT+PCS coincidence.

Eff_{jb} = The geometric efficiency for the Just- β events. This is defined as the fraction of events above the Čerenkov threshold that produce a PMT+PCS coincidence.

$faja$ = The fraction of true Just- α α 's that have an amplitude exceeding the ULD.

x = The fraction of the decays occurring at the wire for which the nucleus recoils into the active volume of the PCS, and eventually ends up on the walls.

Quantities found in Fit Program

t_s = The separation time between the β and α in a DC event.

t_m = This is the maximum t_s for which a DC event can be classified. If $t_s > t_m$ then the α is not observed.

τ_{cut} = The minimum t_s for a β and α to be classified as a delayed coincidence event

$f1$ = The fraction of DC events left after τ_{cut} is imposed

$f6$ = The fraction of DC events with β and α separation τ_s greater than 5000 ns so that it is not classified if the EDM technique is utilized. This may be more if the CDM technique is utilized.

$f2$ = Fraction of DC events above the Čerenkov threshold

$f4$ = The fraction of Just- β events above Čerenkov threshold

$f5$ = The 64% ^{212}Bi branching ratio

$f7$ = The fraction of DC events which survive the wire

$f13$ = The Branching of $^{224}\text{Ra} \rightarrow ^{220}\text{Rn}^*$

$f11$ = The Branching of $^{228}\text{Th} \rightarrow ^{224}\text{Ra}^*$

$f15$ = The Branching of $^{212}\text{Bi} \rightarrow ^{208}\text{Tl}^*$

$f20$ = The fraction of $^{228}\text{Th} \rightarrow ^{224}\text{Ra}^*$ events which produce an electron

$f21$ = The fraction of $^{212}\text{Bi} \rightarrow ^{208}\text{Tl}^*$ events which produce an electron

$f22$ = The fraction of $^{224}\text{Ra} \rightarrow ^{220}\text{Rn}^*$ events which produce an electron

$f32$ = The fraction of $^{228}\text{Th} \rightarrow ^{224}\text{Ra}$ alphas that survive the wire

$f14$ = The fraction of $^{224}\text{Ra} \rightarrow ^{220}\text{Rn}$ alphas that survive the wire

$f17$ = The fraction of $^{220}\text{Rn} \rightarrow ^{216}\text{Po}$ alphas that survive the wire

$f18$ = The fraction of $^{216}\text{Po} \rightarrow ^{212}\text{Pb}$ alphas that survive the wire

fl6= The fraction of $^{212}\text{Bi} \rightarrow ^{208}\text{Tl}$ alphas that survive the wire

fljb= The Fraction of Just- β β events above LLD

fldc= The Fraction of DC β events above LLD

fhjb= The Fraction of Just- β β events above ULD

fhdc= The Fraction of DC β events above ULD

fwall= The fraction of α 's and β 's that enter the active volume of the PCS when the parent nuclei are present on the wall.

rns= The nuclear recoil correction for the n'th α decay

jbwi= The total fraction of the original amount of ^{228}Th left on the wire that may decay and be detected as a true Just- β event.

jbwa= The total fraction of the original amount of ^{228}Th on the walls that may decay and be detected as a true Just- β event.

jawi= The total fraction of the original amount of ^{228}Th left on the wire that may decay and be detected as a true Just- α event.

jawi_wire= The total fraction of the original amount of ^{228}Th left on the wire that will be detected as a Just- α event.

jawa= The total fraction of the original amount of ^{228}Th on the walls that may decay and be detected as a true Just- α event.

dewi= The total fraction of the original amount of ^{228}Th left on the wire that may decay and be detected as a true DC' event.

dewa= The total fraction of the original amount of ^{228}Th on the wall that may decay and be detected as a true Just- β event.

jbwi= The total fraction of the original amount of ^{228}Th left on the wire that may decay and be detected as a true Just- β event.

Backgrounds

dcbg= Background to the DC' measurement

bbg= Background to the Just- β measurement

abg= Background to the Just- α measurement

cjb_bg= Background to the PCS+PMT+Just- β measurement

Appendix C

The Event Classification

Program: CDManalysis.f

```
program CDManalys
```

```
IMPLICIT NONE
```

- * This program classifies event types as JB,JA or DC
- * it also calculates the amplitude of the particle as observed by
- * the PCS

```
real*8 vam,vom(1000),trigg,x(1000),y(1000),slch
real*8 ti(1000),vo(1000),d_vo(1000),dd_vo(1000),ddd_vo(1000)
real*8 slope(1000),av_sl,vmax,vmin,vo1(1000)
real*8 f2m,f2p,f1m,f1p,f0,expression1,expression2
real*8 h,nt,expression3,lldv,uldv
real*8 ns,tip1,tip2,tip3,tip4,tip5,fin,np,p,pp
real*8 n,fp,ms,m1,noise,lovomax,lodvmax,factor
real*8 dtrigg,dvmax,dvmin,dnoise,tau_s,tau_cut,tau_cut1
integer*4 f,m,i,j,k,l,ni,peak_count,nis,nk,init
integer*4 kpeak,lookbk,vmax_sf,vomax_sf1,timax_sf1
integer*4 peaktrigg,dpeaktrigg,dlookbk,dpeakm,no_dp
integer*4 dp,dp1,dp2,go5000,trpeak,dtrpeak,s
integer event,channel,pri,rt,pc1,pc2,ntot
```

- * Changes November 8'95

```
real*8 peakv,d_vom(1000),ph_peak,ph_peak1
&,ph_peak2,width,sv,percent,p1,p2,r1,r2,approx_max_vo
&,true_startpeak,voa,voa2,sv1,sv3,sv4,risetime,ph_at_peak
&,ph_peak1b,ph_peak2a,vamo,ph_peak1c
integer startpeak,endpeak,i1,i2,i3,nc,dlookfwd,lookfwd
&,peak,dms,q,ch,biz,done,gotoch,endset,endpeak1,p3,p5
&,startpeak2,p6,p7,dms2
character*3 eventstring
```

```

character*9 vu
character*10 date,time
character*3 name1,name3,name4,name
character*8 ext
character*14 filename

real*8 uld_setting,tip12,slp,yint,y1,nst,vmax2,vmin2
integer event_type,startpeak1,no_peak,inc,inc1
real*8 v1(1000),d_v1(1000),noise1,d_noise1
real*8 v4(1000),d_v4(1000),noise4,d_noise4
real*8 v3(1000),d_v3(1000),noise3,d_noise3
real*8 slp_b,yint_b,x1b(1000),y1b(1000),y1b_proj
real*8 slp_a,yint_a,x1a(1000),y1a(1000),y1a_proj
real*8 angle,xca,xcb,yca,ycb,mag_a,mag_b,argument
&,ratio(1000),ph_peak1a,d_v1t(1000),d_v3t(1000),d_v4t(1000),
&vam1,discriminator
integer number_of_increases,peak_watch,ph,ph1c,ph2c,
&point,sigma,startset,i4,jb,ja,dc,tau_cut2,total_events

name1="c1-"
name3="c3-"
name4="c4-"

ext=".wk1.con"

open (60,file='f60.dat',status='unknown')
open (61,file='f61.dat',status='unknown')
open (62,file='f62.dat',status='unknown')
open (63,file='f63.dat',status='unknown')
open (64,file='f64.dat',status='unknown')

```

```

open (66,file='f66.dat',status='unknown')
open (65,file='f65.dat',status='unknown')
open (67,file='f67.dat',status='unknown')
open (68,file='f68.dat',status='unknown')
open (69,file='f69.dat',status='unknown')

jb=0
ja=0
dc=0

total_events=500

do 8000 event=100,total_events

*****LOOP OVER NUMBER OF EVENTS*****

=====
*
*           NOTES :
*
=====
*   Channel 1: Is the lowest gain channel ==> Beta
*   channel 3: Next highest ==> High ionization beta
*   channel 4: The highest ==> Alpha's that saturate the scope.

*   Initializing variables:
    channel=0.d0
    biz=0
    do i=1,ns-3
      vo(i)=0.d0
      d_vo(i)=0.d0
      vom(i)=0.d0
      d_vom(i)=0.d0
    enddo
    dnoise=0.d0
    dtrigg=0.d0

```

```

trigg=0.d0
ms=15
p1=0.d0
done=0
approx_max_vo=0.d0
voa=0.d0
tip1=1.d0
tip2=1.d0
tip12=1.d0
no_peak=0
ph_peak1=0.d0
ph_peak1a=0.d0
ph_peak2=0.d0
ph_peak2a=0.d0
event_type=0
discriminator=0.5d0 ! in Volts
tau_cut=300.d-9 ! 300 ns
tau_cut2=200.d-9 ! 200 ns
tau_cut1=100.d-9 ! 100 ns

do 7000 channel=1,4
*****LOOP OVER NUMBER OF CHANNELS*****
    if (biz.eq.1.or.done.eq.1) goto 7000

    vmax=0.d0
    vmin=0.d0
    dvmax=0.d0
    dvmin=0.d0
    sv=0.d0
    p2=0.d0

```

```

lookbk=50
close (10)
if (channel.eq.2) goto 7000
if (channel.eq.1) then
name=name1
else
endif
if (channel.eq.3) then
name=name3
else
endif
if (channel.eq.4) then
name=name4
else
endif

write (eventstring,10) event
10  format(i3)
   filename=name//eventstring//ext
c   write (*,*), 'Reading..filename,channel ==>',filename,channel
c   write (5,*), 'Reading..filename,channel ==>',filename,channel
   open (10,file=filename,status='unknown')
   ns=500  ! Number of times event is sampled
*   Reading the sampled wave form
   do i=1,ns
   if (channel.eq.1) then
   read (10,*) ti(i),v1(i)
   else
   endif
   if (channel.eq.3) then

```

```

      read (10,*) ti(i),v3(i)
      !overkill since ti is already read!
    else
    endif
    if (channel.eq.4) then
      read (10,*) ti(i),v4(i)
      !overkill since ti is already read!
    else
    endif
  enddo

  point=0
  vmax=-4.d0
  vmin=4.d0
  do i=1,50
    if (v1(i).gt.vmax) then
      vmax=v1(i)
    else
    endif
    if (v1(i).lt.vmin) then
      vmin=v1(i)
    else
    endif
  enddo

c    write (*,*),'vmax,vmin',vmax,vmin
  noise=0.d0
  noise=abs(vmax-vmin)
  trigg=vmax+2.d0*noise

7000 continue

```

```
*****
```

```
* AT THIS POINT WE HAVE DETERMINED : NOISE,TRIGG
```

```
* We can set the trigger threshold (TRIGG)
```

```
* just above the noise.
```

```
*****
```

```
* Peak searching algorythm
```

```
  p=0
```

```
  fin=0
```

```
  do k=3,ns-3 ! Loop over number of data points
```

```
    if (fin.eq.1) goto 7100
```

```
    vam=-1.d18 ! A tiny number
```

```
* Generates maximum for ms consecutive vo's
```

```
* in this way we allow for statistical fluctuations.
```

```
  do i=1,ms
```

```
    if (v1(k+i).gt.vam) then
```

```
      vam=v1(k+i)
```

```
    else
```

```
    endif
```

```
  enddo ! End of loop over ms
```

```
  vom(k)=vam ! For each l a max vo has been found
```

```
* We now have an array of the maximum voltage for every ms points.
```

```
  if(
```

```
& vom(k).gt.trigg.and. ! vo is gt osc. trigger
```

```
& p.eq.0.d0 ! peak search turned on
```

```
& ) then ! C
```



```

    p=1.d0 ! Hump searching parameter p is set to 1 to indicate that a
*           peak has been found
    peaktrigg=k ! really the voltage from k to k+ms.
c    write (*,*), 'Peak has been found at ', ti(k), v1(k)
    fin=1
    else
    endif
7100 continue
    enddo

*****

    if (p.eq.1.0d0) then ! First hump condition,

    peak_count=peak_count+1
c    write (*,*), 'peak_count==>', peak_count
*    NOTE: Also slightly redundant! but more exact!
*    We need to find out for which k the vo went below the
*    maximum of the noise. This we can consider to be the
*    real start of the hump.
    do i=(peaktrigg-lookbk), (peaktrigg+ms)
    if (v1(i).le.vmax) then
    startpeak=i
c    write (*,*), 'startpeak', i, v1(i)
    else
    endif
    enddo

*    The last kpeak will be the last k which is below the max
*    range of the noise
*    Thus the true tip1=ti(startpeak)
    tip1=ti(startpeak)
c    write (*,*), 'We have found the first hump !'

```

```

c      write (*,*), 'at time', tip1
c      write (5,*), 'The true start of the peak is at', tip1, ti(startpeak)
c      &, startpeak, k
c      write (5,*), 'We have found the first hump !'
c      write (5,*), 'at time', tip1

```

```

else
endif

```

```

*****

```

```

*           We have found the first hump           *

```

```

*****

```

```

*=====

```

```

! PEAK SEARCHING ALGORITHM WORKS BY LOOKING FOR
! AN INCREASE IN SLOPE AFTER A REFERENCE POINT!

```

```

sv1=1.55d-1      ! [
sv3=1.49d0       ! {   These are for events without PMT coincidence
sv4=4.21d0       ! [

```

```

*   The saturation voltages are different for different voltage scales.

```

```

*   sv1=1.36d-1  ! [
*   sv3=1.41d0   ! {   These are for PMT Coincidence events
*   sv4=3.69d0   ! [

```

```

trigg=3.5d0    ! Set to large number
dms=10         ! voltage differences checked 10 points before and 10 points
dms2=7         ! before, and 10 points after reference point.
ntot=4
ch=0
number_of_increases=0
peak_watch=0
done=0
startpeak2=0
tip12=1.d0
tip2=1.d0

do i1=(startpeak+dms2),ns-3
  if (ch.eq.3.or.done.eq.1) goto 7700
  y1b(i1)=v1(i1+dms)-v1(i1)
  y1a(i1)=v1(i1+2*dms)-v1(i1+dms)
c   write (*,*) ,ti(i1+dms),y1a(i1),y1b(i1)
  if (y1b(i1).ne.0) then
    if (y1a(i1).lt.0.d0) then
c      write (*,*) ,ti(i1+dms),(y1a(i1)/y1b(i1)),y1a(i1)
    else
c      write (*,*) ,ti(i1+dms),(y1a(i1)/y1b(i1)),y1a(i1),'*'
    endif
    ratio(i1)=y1a(i1)/y1b(i1)

*      IT IS THE RATIO OF THE VOLTAGE DIFFERENCE 10 POINTS BEFORE AND
*      AFTER THE REFERENCE POINT THAT IS COMPARED.

    if (peak_watch.eq.1.and.
&ratio(i1).gt.(0.5d0*ratio(i1-1)).and.

```

```

      &ratio(i1).gt.trigg.and.y1a(i1).gt.0.d0) then
*! ADDED NOV 29'95 ! to prevent peaks on downward trend.
      number_of_increases=number_of_increases+1
*      Currently set to 1, but can demand a number of increases in the
*      ratio before it is decided that a peak is found. Due to steep
*      peaks (or long time intervals/div) this is set to 1.

c      write (*,*),'number of increases..',number_of_increases
      else
      endif
      if (number_of_increases.eq.ntot) then
          !We have a peak!
c      write (*,*),'we have a peak!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      startpeak2=i1+ntot
      done=1
      else
      endif
      if (ratio(i1).gt.trigg) then
      peak_watch=1
      else
      peak_watch=0
      number_of_increases=0
      endif
      else
      endif

      if (v1(i1+dms+1).eq.sv1) then
      ch=3
      nc=i1+dms+1

```

```

        else
        endif
7700 continue
        enddo

c      write (*,*), 'Going on to channel 3!'

*      SAME ANALYSIS FOR CHANNEL 3:

do i1=(startpeak+dms2),ns-3
  if (ch.eq.4.or.done.eq.1) goto 7750
  y1b(i1)=v3(i1+dms)-v3(i1)
  y1a(i1)=v3(i1+2*dms)-v3(i1+dms)
c    write (*,*),ti(i1+dms),y1a(i1),y1b(i1)
  if (y1b(i1).ne.0) then
c      write (*,*),ti(i1+dms),(y1a(i1)/y1b(i1))
      ratio(i1)=y1a(i1)/y1b(i1)
      if (peak_watch.eq.1.and.
&ratio(i1).gt.(0.5d0*ratio(i1-1)).and.
&ratio(i1).gt.trigg.and.y1a(i1).gt.0.d0) then
*! ADDED NOV 29'95 ! to prevent peaks on downward trend.
      number_of_increases=number_of_increases+1
c      write (*,*), 'number of increases..',number_of_increases
      else
      endif
      if (number_of_increases.eq.ntot) then
          !We have a peak!
c      write (*,*), 'we have a peak!!!!!!!!!!!!!!!!!!!!!!!!!!!!'

```

```

        startpeak2=i1+ntot
        done=1
        else
        endif
        if (ratio(i1).gt.trigg) then
        peak_watch=1
        else
        peak_watch=0
        number_of_increases=0
        endif
    else
    endif

    if (v3(i1+dms+1).eq.sv3) then
    ch=4
    nc=i1+dms+1
    else
    endif

7750 continue
    enddo

c      write (*,*), 'Going on to channel 4!'

*      SAME ANALYSIS FOR CHANNEL 4:

do i1=(startpeak+dms2),ns-3
    if (ch.eq.5.or.done.eq.1) goto 7775
    y1b(i1)=v4(i1+dms)-v4(i1)
    y1a(i1)=v4(i1+2*dms)-v4(i1+dms)

```

```

c      write (*,*),ti(i1+dms),yla(i1),y1b(i1)
      if (y1b(i1).ne.0) then
c          write (*,*),ti(i1+dms),(yla(i1)/y1b(i1))
          ratio(i1)=yla(i1)/y1b(i1)
          if (peak_watch.eq.1.and.
&ratio(i1).gt.(0.5d0*ratio(i1-1)).and.
&ratio(i1).gt.trigg.and.yla(i1).gt.0.d0) then
*! ADDED NOV 29'95 ! to prevent peaks on downward trend.
          number_of_increases=number_of_increases+1
c          write (*,*),'number of increases..',number_of_increases
          else
          endif
          if (number_of_increases.eq.ntot) then
              !We have a peak!
c          write (*,*),'we have a peak!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
          done=1
          startpeak2=i1+ntot
          else
          endif
          if (ratio(i1).gt.trigg) then
              peak_watch=1
          else
              peak_watch=0
              number_of_increases=0
          endif
          else
          endif

          if (v4(i1+dms+1).eq.sv4) then
              ch=5

```

```

        else
        endif

7775  continue
      enddo

*****

c      write (*,*),'finished! ',ti(startpeak2)
      tip1=ti(startpeak)
      if (startpeak2.eq.0.or.
&ti(startpeak2).gt.ti(480)) then
      tip2=1.d0
      tip12=1.d0
      else
      tip2=ti(startpeak2+dms)
      endif
c      write (*,*),'tip1,tip2...',tip1,tip2
      tip12=tip2-tip1
      trigg=0.d0
      done=0

*****

      ! CALCULATION OF PULSE HEIGHTS !
      ! METHOD 1 !

*      CRUDE METHOD: DETERMINES PULSE HEIGHT BY FINDING THE VOLTAGE
*      AT A POINT, LOOKFWD AWAY FROM THE START OF THE PEAK.

```



```

c      write (*,*),'tip12....',tip12

      if (tip12.ne.1.d0.and.tip12.lt.300.d-9) then
      ph=startpeak2-5
c      write (*,*),'ph=startpeak2-5'
      else
      lookfwd=30
      ph=startpeak+lookfwd
c      write (*,*),'ph=startpeak+lookfwd'
      endif
      ph1c=0
      ph2c=0

      if (v1(ph).ne.sv1) then
*      v1(ph) must be lower than sv1, since sv1 is max.
      ph_peak1a=v1(ph)
      ph1c=1
      else
        if (v3(ph).ne.sv3) then
*      v3(ph) must be lower than sv3, since sv3 is max.
        ! and it can not be smaller than sv1
        ph_peak1a=v3(ph)
        ph1c=3
        else
          if (v4(ph).ne.sv4) then
*      v4(ph) must be between sv3 and sv4
          ph_peak1a=v4(ph)
          ph1c=4
          else
            endif

```

```

        endif
    endif
c    write (*,*),v1(ph),v3(ph),v4(ph),ph_peak1,ph1c

    if (startpeak2.ne.0) then
    ph=startpeak2+50
    if (v1(ph).ne.sv1) then
*    v1(ph) must be lower than sv1, since sv1 is max.
    ph_peak2a=v1(ph)
    ph2c=1
    else
        if (v3(ph).ne.sv3) then
*    v3(ph) must be lower than sv3, since sv3 is max.
        ! and it can not be smaller than sv1
        ph_peak2a=v3(ph)
        ph2c=3
        else
            if (v4(ph).ne.sv4) then
*    v4(ph) must be between sv3 and sv4
            ph_peak2a=v4(ph)
            ph2c=4
            else
                endif
            endif
        endif
    endif
    endif
    else
c    write (*,*),'There is no second peak'
    endif
c    write (*,*),v1(ph),v3(ph),v4(ph),ph_peak2a,ph2c

```

! CALCULATION OF PULSE HEIGHTS !

! METHOD 2 !

* THIS TECHNIQUE WORKS BY LOOKING FOR A MAXIMUM IN THE NEXT
 * PEAK. THEN IT CALCULATES THE VOLTAGE A BIT FURTHER FROM THE
 * PEAK.

endset=ns-5

vam=-4.d0

vamo=0.d0

fin=0

point=0

sigma=0

endset=ns-5

if (ph2c.ne.0) then

startset=startpeak2

else

startset=startpeak

ph2c=ph1c

endif

if (ph2c.eq.1) then

do i=startset,endset

if (i.gt.(startset+1)) then

d_v1(i)=v1(i)-v1(i-1)

if (d_v1(i).ge.vam) then

vam=d_v1(i)

```

        peak=i
    else
    endif
else
endif
enddo
c    write (*,*), 'peak...', ti(peak), v1(peak)
    if (peak.gt.startset) then
        sigma=peak-startset
    else
        peak=0
        sigma=0
    endif
    ph_peak2=v1(peak+2.d0*sigma)
    if (ph_peak2.eq.sv1) then
        ph_peak2=v3(peak+2.d0*sigma)
    else
    endif
c    write (*,*), '==> sigma', sigma, v1(peak+2.d0*sigma)
    else
    endif

vam=-4.d0
vamo=0.d0
fin=0
if (ph2c.eq.3) then
    do i=startset, endset
        if (i.gt.(startset+1)) then
            d_v3(i)=v3(i)-v3(i-1)
            if (d_v3(i).ge.vam) then

```

```

        vam=d_v3(i)
        peak=i
        else
        endif
    else
    endif
enddo
if (peak.gt.startset) then
sigma=peak-startset
else
peak=0
sigma=0
endif
ph_peak2=v3(peak+2.d0*sigma)
if (ph_peak2.eq.sv3) then
ph_peak2=v4(peak+2.d0*sigma)
else
endif
c    write (*,*), '==> sigma',sigma,v3(peak+2.d0*sigma)
else
endif

vam=-4.d0
vamo=0.d0
if (ph2c.eq.4) then
do i=startset,endset
    if (i.gt.(startset+1)) then
        d_v4(i)=v4(i)-v4(i-1)
        if (d_v4(i).ge.vam) then
            vam=d_v4(i)

```

```

        peak=i
    else
    endif
else
endif
enddo
c    write (*,*),'peak...',ti(peak),v4(peak)
    if (peak.gt.startset) then
        sigma=peak-startset
    else
        peak=0
        sigma=0
    endif
    ph_peak2=v4(peak+2.d0*sigma)
c    write (*,*),'==> sigma',sigma,v4(peak+2.d0*sigma)
    else
    endif

*    LOOK FOR PROBLEMS IN THE AMPLITUDE MEASUREMENTS. IF THE SPREAD
*    IN THE DIFFERENTIATED HUMP IS MUCH LONGER THAN EXPECTED THE
*    MORE CRUDE (BUT RELIABLE) METHOD 1 IS USED.

    if (sigma.gt.150) then
        ! probably not a good measurement of the pulse height
        ! thus we accept method 1 analysis
        peak=0
    else
    endif

```

```

      if (ti(peak).gt.ti(480)) then
        ! This is probably a very slow rise time beta so that
        ! method 2 is not reliable
        ! thus we accept method 1 analysis
        tip12=1.d0
        tip2=1.d0
        peak=0
      else
        endif

      if (tip2.ne.1.d0.and.tip12.lt.ti(480).and.
&tip12.gt.tau_cut1) then
*      A second peak is observed
        event_type=3
        if (peak.ne.0) then
          ! We accept the method 1 measurement of first peak
          ! and take the method 2 measurement of the second peak
          ph_peak1=ph_peak1a
c      write (*,*), 'Method1,2..ph_peak1,ph_peak2',ph_peak1,ph_peak2
        else
          ! We have a slow rise-time event at which method 2 is not
          ! reliable. Thus we accept method 1 for both peaks.
          ph_peak1=ph_peak1a
          ph_peak2=ph_peak2a
c      write (*,*), 'Method1..ph_peak1,ph_peak2',ph_peak1,ph_peak2
        endif
      else
*      No second peak is observed
        if (peak.ne.0) then
          ph_peak1=ph_peak2

```

```

c      write (*,*), 'Method2..ph_peak1', ph_peak1
      else
        ph_peak1=ph_peak1a
c      write (*,*), 'Method1..ph_peak1', ph_peak1a
      endif
      ph_peak2=0.d0
      endif

c      write (*,*), 'Start writing filenames to a file for graphical
c      & output'

      if ((ph_peak2.lt.0.5.and.ph_peak2.gt.0.d0).or.
&(ph_peak1.eq.sv1.or.
&ph_peak1.eq.sv3.or.
&ph_peak1.eq.sv4)) then
        write (*,*), 'ph_peak1,ph_peak2..', ph_peak1, ph_peak2
        point=1
      else
      endif

      if (event_type.eq.0.or.event_type.eq.5) then

tip2=1.d0      ! Throw the arrow way off graph
tip12=1.d0     ! Separation of alpha and beta
               ! However no second particle present
               ! thus set = 0 as a indicator, it is not the
               ! the actual separation.

*      SETS ARROW FOR PAW TO PLOT ON GRAPH, WHERE IN TIME THE
*      PEAKS WERE DETERMINED.

```



```

c      write (*,*), 'ph_peak1, discr', ph_peak1, discriminator
        if (ph_peak1.lt.discriminator) then
            event_type=1
        else
            event_type=2
        endif

    else

*      must be event type 3, ie. a delayed coincidence event.
        tip12=tip2-tip1
        write (4,*), tip12
    endif

*      IF THERE IS A SIZABLE NEGATIVE PULSE, IT MUST BE NOISE.

        do i4=1, ns-3
            if (v1(i4).lt.(vmin-1.5d0*noise)) then
                write (*,*), 'This event is NOISE!!!'
                event_type=5
                tip1=1.d0
                tip2=1.d0
                tip12=1.d0
            else
            endif
        enddo

        if (event_type.eq.5) then
            write (1,*), event
        else
        endif

        write (*,*), 'event, event_type', event, event_type

```

```

        write (*,*), 'ph_peak1,ph_peak2',ph_peak1,ph_peak2
        write (*,*), 'tip12',tip12
c      write (*,*), 'EVENT TYPE ::::::::::::::',event_type
        write (8,*),ph_peak1

c      print *, 'Do you want to have a graphical display (yes=1,no=0)'
c      read *,point
c      if (point.ne.1) then
c      goto 7900
c      else
c      point=0
c      endif

        do 7800 channel=1,4
*****LOOP OVER NUMBER OF CHANNELS*****
        close (10)
        if (channel.eq.2) goto 7800
        if (channel.eq.1) then
            name=name1
            open (11,file='f11.dat',status='unknown')
            open (12,file='f12.dat',status='unknown')
            open (14,file='f14.dat',status='unknown')
        else
            endif
        if (channel.eq.3) then
            name=name3
            open (31,file='f31.dat',status='unknown')
            open (32,file='f32.dat',status='unknown')
            open (34,file='f34.dat',status='unknown')
        else

```

```

endif
if (channel.eq.4) then
name=name4
open (41,file='f41.dat',status='unknown')
open (42,file='f42.dat',status='unknown')
open (44,file='f44.dat',status='unknown')
else
endif

write (eventstring,7500) event
7500 format(i3)
filename=name//eventstring//ext
c   write (*,*),'Reading..filename,channel ==>',filename,channel
c   write (5,*),'Reading..filename,channel ==>',filename,channel
open (10,file=filename,status='unknown')
ns=500 ! Number of times event is sampled
*   Reading the sampled wave form

do i=1,500
read (10,*) ti(i),vo(i)
enddo

nt=1 ! Differentiating every nt steps
h=ti(nt+1)-ti(1)
c   write (*,*),'Differentiation is done every',nt,'time units'
c   write (5,*),'Differentiation is done every',nt,'time units'

*****
*   Calculating the first,second and third derivatives

```

```

*   with a five point formula that allows sensitivity
*   to interpolation of a fourth order polynomial.
do j=3,ns-3
  f2m=0.
  f2p=0.
  f1p=0.
  f2p=0.
  f0= 0.
  f2m=vo(j-2)
  f1m=vo(j-1)
  f0=vo(j)
  f1p=vo(j+1)
  f2p=vo(j+2)
  expression1=f2m-8.*f1m+8.*f1p-f2p
  expression2=-1*f2m+16.*f1m-30.*f0+1*f1p-f2p
  expression3=(-1.*f2m+2.*f1m-2*f1p+f2p)
  d_vo(j)=(1./(12.*h))*expression1
  dd_vo(j)=(1./(12.*h*h))*expression2
  ddd_vo(j)=(1./(2.*h*h*h))*expression3
  pri=10
  if (channel.eq.1) then
    write (pri+1,*),ti(j)
    write (pri+2,*),vo(j)
    write (pri+4,*),d_vo(j)
  else
    endif
  if (channel.eq.3) then
    write (pri+1+20,*),ti(j)
    write (pri+2+20,*),vo(j)
    write (pri+4+20,*),d_vo(j)

```

```

else
endif
if (channel.eq.4) then
write (pri+1+30,*),ti(j)
write (pri+2+30,*),vo(j)
write (pri+4+30,*),d_vo(j)
else
endif
enddo

```

```

*****

```

```

7800 continue
7900 continue
close(11)
close(12)
close(14)
close(31)
close(32)
close(34)
close(41)
close(42)
close(44)

open (50,file='times',status='unknown')
write (50,*),tip1
write (50,*),tip2
write (50,*),tip12
close (50)
if (event_type.eq.1) then

```

```
write (61,*),ph_peak1
jb=jb+1
else
endif
if (event_type.eq.2) then
ja=ja+1
write (62,*),ph_peak1
else
endif
if (event_type.eq.1.or.event_type.eq.2) then
write (60,*),ph_peak1
write (68,*),tip1
else
endif
if (event_type.eq.3) then
dc=dc+1
write (63,*),ph_peak1
write (64,*),ph_peak2
write (65,*),tip12
if (tip12.gt.tau_cut) then
write (67,*),tip12
write (66,*),ph_peak2
else
endif
if (tip12.gt.tau_cut2) then
write (69,*),ph_peak2
else
endif

else
```

```

endif

open (7,file='rf',status='unknown')
write (7,*),(event+(event_type/10.))
close(7)

      write (*,*),'          *****'
      write (*,*),event_type
      write (*,*),event,tip1,ph_peak1
      write (*,*),event,tip2,ph_peak2

if (event_type.eq.3) then
  call system ('pawscript')
*   PAWSRIPT is a script file that calls a PAW analysis program
*   plots the data, and prints it, if desired.
  write (*,*),event,'  analysed and printed...'
  write (*,*),event,'  fort.* files deleted...'
  else
endif

7999 continue

8000 continue ! END OF LOOP OVER EVENT
      write (3,*),'jb,ja,dc',jb,ja,dc
      write (*,*),'jb,ja,dc',jb,ja,dc

*****

      close (10)
      close (60)
      close (61)
      close (62)
      close (63)
      close (64)
      close (65)

```

```
close (66)  
close (67)  
close (98)  
end
```


Appendix D

The Fitting Program: GORECKI.f

PROGRAM GORECKI

C 5 PARAMETER FIT UTILIZING MINUIT: act,EFF_dc,EFF_jb,faja,x

C ALL EXPERIMENTAL BG MEASUREMENTS INCLUDED

* NOTE: Wire correcttion includes straggling effects(Fe only) and

* range is fit for 3 component 304 stainless steel.

*

* PROGRAM EXECUTION: f77 -g -o fit1 GORECKI.f -L/local/cern/pro/lib

* -lgenlib -lpacklib -lkernlib

IMPLICIT NONE

INTEGER

* I,J

* ,IERFLG

* ,IVARBL

* ,ISTAT

* ,npf

REAL*8

* FPARA(10)

* ,FSTEP(10)

* ,FMIN(10)

* ,FMAX(10)

* ,er_Etl,Etl,f,er_f,Euld,x,e_x

* ,er_Euld,fhdc,fhjb,eff_jb,eff_dc,e_eff_jb,e_eff_dc

* ,e_fhjb,e_fhdc,fadc,e_fadc,fajb,e_fajb,e_act,e_faja

* ,faja

CHARACTER*10 FNAM(10),CHNAM

DATA (FNAM(I),I=1,5) /'act','dc_eff','jb_eff','faja','x' /

REAL*8

* R(15),ER(15),EX(15),EXER(15)

INTEGER NDIM

REAL*8

```
*      FVAL
*      ,BND1,BND2
*      ,DUMARG(1)
*      ,FEDM
*      ,ERRDEF
*      ,NPARI,NPARX
```

real*8

```
*      act,
*      EFF,
*      a_bg,
*      b_bg,
*      er_act,
*      er_eff,
*      er_a_bg,
*      er_b_bg,
*      f23,
*      er_f23,cjb_bg,c_bg
```

real*8

```
*      F1p,F2p,F3p,F4p,F5p,F6p,
*      chi(15),
*      er_f1p,er_f2p,er_f3p,er_f4p,er_f5p,er_f6p,
*      er_m,er_dif,er_dif3,er_m3,er_m4,er_m5,er_d
*      ,fp,er_fp
```

COMMON /FITPAR/ R,ER,EX,EXER,NDIM

EXTERNAL FITIT

EX(1)=0.9728d0

EX(2)=0.051052d0

EX(3)=1.081104d0

```

EX(4)=1.0521d-3
EX(5)=0.022196d0
EX(6)=7.5156d-4
EX(7)=2.105d0
R(1)=EX(1)
R(2)=EX(2)
R(3)=EX(3)
R(4)=EX(4)
R(5)=EX(5)
R(6)=EX(6)
R(7)=EX(7)
EXER(1)=0.03d0*ex(1)
EXER(2)=0.14d0*ex(2)
EXER(3)=0.03d0*ex(3)
EXER(4)=0.15*ex(4)
EXER(5)=0.03*ex(5)
EXER(6)=0.18*ex(6)
EXER(7)=0.022d0*ex(7)
ER(1)=EXER(1)
ER(2)=EXER(2)
ER(3)=EXER(3)
ER(4)=EXER(4)
ER(5)=EXER(5)
ER(6)=EXER(6)
ER(7)=EXER(7)
do i=1,7
  write (*,*), 'er', i, ' : ', er(i)
enddo
NDIM = 7
npf=5

```

```

c      call ERANAL(ER,R)
do i=1,7
write (6,*),'error is for eqn ',i, ' :: ',ER(i)
write (6,*),'exptl value is for eqn ',i, ' :: ',R(i)
enddo

      FPARA(1) = 0.35D0          ! OUR INITIAL GUESS AT act
      FPARA(2) = 0.01D0          ! OUR INITIAL GUESS AT EFF_dc
      FPARA(3) = 0.06D0          ! OUR INITIAL GUESS AT EFF_jb
      FPARA(4) = 0.74D0          ! OUR INITIAL GUESS AT faja
      FPARA(5) = 0.48D0          ! OUR INITIAL GUESS AT x

      FSTEP(1) = 0.2D0           ! OUR INITIAL ROUGH GUESS AT ERROR act
      FSTEP(2) = 0.05D0          ! OUR INITIAL ROUGH GUESS AT ERROR Eff_dc
      FSTEP(3) = 0.05D0          ! OUR INITIAL ROUGH GUESS AT ERROR Eff_jb
      FSTEP(4) = 0.2D0           ! OUR INITIAL ROUGH GUESS AT ERROR faja
      FSTEP(5) = 0.2D0           ! OUR INITIAL ROUGH GUESS AT ERROR x

      FMIN(1)  = 0.0D0
      FMIN(2)  = 0.0D0
      FMIN(3)  = 0.0D0
      FMIN(4)  = 0.0D0
      FMIN(5)  = 0.0D0

      FMAX(1)  = +1.0D0
      FMAX(2)  = +1.0D0
      FMAX(3)  = +1.0d0
      FMAX(4)  = +1.0d0
      FMAX(5)  = +1.0d0

```

```

*****
*   MNINIT      INITIALIZES MINUIT BY TELLING WHAT UNITS TO OUTPUT TO
*   MNPARM      FEEDS MINUIT THE INITIAL GUESSES AT THE PARAMETERS
*                AND THE INITIAL GUESSES AT THE UNCERTAINTIES.

*   MNSETI      GIVES MINUIT THE TITLE OF THE FIT
*   MNEXCM      'SET PRINT' TELLS MINUIT HOW MUCH OUTPUT YOU WANT TO
*                SEE.  1.0D0 GIVES THE MAX, -1.0D0 GIVES
*                MINIMUM AMOUNT OF OUTPUT.
*                'CALL FITIT' 1.0D0 IS THE INITIAL CALL, GETS THE
*                VALUE OF CHI**2 GIVEN THE INITIAL GUESSES.
*                3.0D0 IS THE FINAL CALL, GETS THE VALUE
*                OF CHI**2 GIVEN THE FINAL RESULTS OF THE
*                FIT.
*                'MINIMIZE' TELLS MINUIT TO MINIMIZE THE CHI**2.
*                'EXIT' TELLS MINUIT YOU ARE FINISHED FITTING.
*   MNPOUT      ALLOWS YOU TO ACCESS THE RESULTS OF THE FIT.
*   MNSTAT      ALLOWS YOU TO ACCESS THE STATUS OF THE FIT.  IF
*                ISTAT=3, THE FIT HAS CONVERGED.  OTHERWISE, IT HAS
*                NOT.  FVAL WILL BE THE VALUE OF THE CHI**2 FROM THE FIT.
*****

```

```
CALL MNINIT(5,6,7)
```

```
DO 100 J = 1,npf
```

```
CALL MNPARM(J,FNAM(J),FPARA(J),FSTEP(J),FMIN(J),FMAX(J),IERFLG)
```

```
100 CONTINUE
```

```
CALL MNSETI('STRAIGHT LINE FIT')
```

```

DUMARG(1) = +1.0D0
CALL MNEXCM(FITIT,'SET PRINT',DUMARG,1,IERFLG,0)
DUMARG(1) = 1.0D0
CALL MNEXCM(FITIT,'CALL FITIT',DUMARG,1,IERFLG,0)
DUMARG(1) = 5000.0D0
CALL MNEXCM(FITIT,'MINIMIZE',DUMARG,1,IERFLG,0)

CALL MNPOUT(1,CHNAM,act,e_act,BND1,BND2,IVARBL)
CALL MNPOUT(2,CHNAM,eff_dc,e_eff_dc,BND1,BND2,IVARBL)
CALL MNPOUT(3,CHNAM,eff_jb,e_eff_jb,BND1,BND2,IVARBL)
CALL MNPOUT(4,CHNAM,faja,e_faja,BND1,BND2,IVARBL)
CALL MNPOUT(5,CHNAM,x,e_x,BND1,BND2,IVARBL)

CALL MNSTAT(FVAL,FEDM,ERRDEF,NPARI,NPARX,ISTAT)
write (6,*),'istat is ...',istat
IF (ISTAT.NE.3) THEN
    WRITE(6,*) 'FERENC: THE FIT DID NOT CONVERGE!'
ELSE
    WRITE(6,*) 'FERENC: THE FIT CONVERGED JUST FINE'

write (6,*),'*****'
write (6,*),'TOTAL chi-squared value is ',fval
write (6,*),'*****'
write (6,*),'measurement for eqn 1 is a',R(1),'+-',ER(1)
write (6,*),'measurement for eqn 2 is a',R(2),'+-',ER(2)
write (6,*),'measurement for eqn 3 is a',R(3),'+-',ER(3)
write (6,*),'measurement for eqn 4 is a',R(4),'+-',ER(4)
write (6,*),'measurement for eqn 5 is a',R(5),'+-',ER(5)
write (6,*),'measurement for eqn 4 is a',R(6),'+-',ER(6)
write (6,*),'measurement for eqn 4 is a',R(7),'+-',ER(7)

```

```

END IF
DUMARG(1) = 3.0D0
CALL MNEXCM(FITIT,'CALL FITIT',DUMARG,1,IERFLG,0)
DUMARG(1) = 0.0D0
CALL MNEXCM(FITIT,'RETURN',DUMARG,1,IERFLG,0)
DUMARG(1) = 0.0D0
CALL MNEXCM(FITIT,'EXIT',DUMARG,1,IERFLG,0)

```

```

STOP

```

```

END

```

```

*****
*****
*****

```

```

SUBROUTINE FITIT(NPAR,GRAD,FVAL,XVAL,IFLAG,FUTIL)

```

```

IMPLICIT NONE

```

```

REAL*8

```

```

*          GRAD(*)
*          ,XVAL(*)
*          ,FUTIL
*          ,FVAL
*          ,Et1

```

```

INTEGER

```

```

*          NPAR
*          ,IFLAG
*          ,I

```


REAL*8

```
*      ACT,EFF_jb,Eff_dc,a_bg,b_bg
*      ,R(15),ER(15),L(15)
*      ,tau_cut,eff
*      ,f1,f2,f3,f4,f5,f6,f7,f8,f9,f10,f11,f12,f13,f14,f15
*      ,f20,f21,f22,f16,f17,f18,f19,f32,fun1,fun2,fun3,fun4
*      ,p1,p2,p3,p4,p5,p6,p7,p8,p9,p10,p11,p12,p13,p14
*      ,pp1,pp2,pp3,pp4,pp5,pp6,pp7,pp8,pp9,pp10,pp11,pp12
*      ,pp13,pp14,pp15
*      ,f(10),Elld,Euld,fadc,faja,fldc,fhdc,fljb,fhjb
*      ,chi,cjb_bg,c_bg,dc_bg,jadotuld,kdc
*      ,EX(15),EXER(15),wall_corr_jb,wall_corr_dc
*      ,wall_corr_ja,x,x2s,x3s,x4s,x5s
*      ,dcwa,dcwi,jawa,jawi,jbwa,jbwi,no_wire,jawi_wire
*      ,fwall
```

INTEGER NDIM

COMMON /FITPAR/ R,ER,EX,EXER,NDIM

```
*      MAIN ROUTINE: These are the quantities that are relevant to a rate anal
*                      the PCS.
```

```
eff_dc=xval(2)
eff_jb=xval(3)
act= xval(1)
faja=xval(4)
x=xval(5)
```

```

dc_bg=(1.053d-3/0.117d0)*EX(2)
b_bg=(0.1709d0/1.858d0)*EX(1)
a_bg=(1.657d-2/2.342d0)*EX(3)
cjb_bg=(2.164d-3/1.3398d-2)*EX(5)*2.67d0
c_bg=(2.226d-3/2.1349d-2)*EX(7)

```

```
tau_cut= 300.D-9
```

```
f1= dexp(-2.3105D-3*tau_cut*1.D9) ! time cut
```

```
f6= 9.636D-6 ! fraction of events with be al sepn gt 5000 ns
```

```
f2=0.848d0 ! fraction of dc events above cer threshold
```

```
f2=0.5d0*f2
```

```
f3=1.36d0 ! number of jb decays/ Th-chain
```

```
f4=0.2686d0 ! fraction of jb events above cer threshold
```

```
f4=1.5d0*f4
```

```
f5=0.64d0 ! Bi-212 branch which goes through the dc
```

```
f7=0.75135d0 ! fraction of dc events which survive the wire
```

```
f8=0.62985d0 ! fraction of ja events which survive wire
```

```
f9=1.d0 ! ? fraction of just beta bg above cer threshold=f23
```

```
f10=4.36d0 ! number of ja decays/ Th-chain
```

```
f13=0.05d0 ! Branching of Ra->(Rn*)
```

```
f11=0.267d0 ! Branching of Th->(Ra*)
```

```
f12=.001d0 ! ? fraction of just alpha bg above cer.
```

```
f15=0.699d0 ! Branching of Bi->(Tl*)
```

```
f20=16.d0/(16.d0+1.d0) ! % of Th->(Ra*) events which produce an e
```

```
f21=22.55d0/(22.55d0+1.d0) ! ditto but for the Bi->(Tl*) transition
```

```
f22=0.17 ! ? not understood what the ratio is for Ra->(Rn*)
```

```
c All wire corrections made Sept. 10 '95
```

```
f32=0.60845d0 ! wire corr. Th228=>Ra224 {alphas that
```

```
f14=0.61668d0 ! wire corr. Ra224=>Rn220 {survive the
```

```
f17=0.6363d0 ! wire corr. Rn220=>Po216 {wire
```

f18=0.6542d0 ! wire corr. Po216=>Pb212
 f16=0.62925d0 ! wire corr. Bi212=>Tl208

f12=0.001d0

f9=0.51727d0 ! or f23

c The six eqns describing the theoretical calcs expect. data

fadc= 1.0d0 ! Fraction of dc a events above uld

c faja= 0.74d0 ! Fraction of ja a events above uld

fljb= 1.0d0 ! Fraction of jb b events above lld

fldc= 1.0d0 ! Fraction of dc b events above lld

fhjb= 0.0d0 ! Fraction of jb b events above uld

fhdc= 0.0d0 ! Fraction of dc b events above uld

* THESE ARE THE WALL CORRECTIONS:

c x=0.475d0

x2s=(1.d0+(1.d0-x))

x3s=(x2s+(1.d0-x)**2.)

x4s=(x3s+(1.d0-x)**3.)

x5s=(x4s+(1.d0-x)**4.)

fwall=0.5d0 ! This is the probability that the particles
 ! decaying at the wall will go into the active
 ! volume of the PCS.

wall_corr_jb=(x/2.d0)*x4s+(1.d0-x)**4.

& +0.36d0*((x/2.d0)*x5s+(1.d0-x)**5.)

! This is the corrected rate for events where a
 ! portion of these decays occur at the wall --

```

! this number is instead of 1.36.
! This is what is detected, not the amount present.
! CHANGE: Dec 6'95
jbwa=(x*x4s)+0.36d0*(x*x5s)
! This is the amount present at the wall
jbwi=(1.d0-x)**4.+0.36d0*((1.d0-x)**5.)
! This is the amount present at the wire

wall_corr_ja=f32+(x/2.d0)+(1.d0-x)*f14+
& (x/2.d0)*x2s+((1.d0-x)**2.)*f17+
& (x/2.d0)*x3s+((1.d0-x)**3.)*f18+
& ((x/2.d0)*x4s+((1.d0-x)**4.)*f16)*0.36d0
! This is the corrected rate for events where a
! portion of these decays occur at the wall --
! this number is instead of 4.36.
! CHANGE: Dec 9'95
jawa=(x)+(x)*x2s+(x)*x3s
& + 0.36d0*(x)*x4s
! This is the amount present at the wall
jawi_wire=f32+(1.d0-x)*f14+
& +((1.d0-x)**2.)*f17
& +((1.d0-x)**3.)*f18
& +((1.d0-x)**4.)*f16*0.36d0
! This is the same as jawa except that this is the amount
! that is detected at the wire. Since the wire correction
! varies for each isotope but the geometrical effect at
! the wall is always 0.5, it is easier to introduce this
! new variable.
jawi=f32+(1.d0-x)+((1.d0-x)**2.)+
& ((1.d0-x)**3.)+((1.d0-x)**4.)*0.36d0

```

! This is the amount present on the wire

wall_corr_dc=((x*x4s)*fwall*fwall +

& ((1.d0-x)**4.)*f7) ! This is what is detected

dcwa=(x*x4s)

! This is the amount present at the wall.

dcwi=((1.d0-x)**4.) ! This is the amount present on the wire

! notice the depletion: if x=0.5 the amount is down to 1/32 of

! original amount on the wire.

write (*,),'wall_corr_dc',wall_corr_dc

write (*,),'wall_corr_jb',wall_corr_jb

write (*,),'wall_corr_ja',wall_corr_ja

no_wire=1.d0 ! This is only to emphasize that no wire

! corection needs to be made.

* THESE ARE THE THEORETICAL EQUATIONS FIT: See equations found in chapte

L(1)=(

& (jbwa*fwall+jbwi*no_wire)*(fljb-fhjb)

&!-----true just-beta events the fraction between LLD and ULD

& +(jawa*fwall+jawi_wire)*(1.d0-faja)

&!-----ja events where the alpha is below the ULD

& + f5*dcwi*((1.d0-f7)+f6+(1.d0-fadc)

& - (1.d0-f7)*f6-f6*(1.d0-fadc)

&)*(fldc-fhdc)

& + f5*dcwa*((1.d0-fwall)+f6+(1.d0-fadc)

& - (1.d0-fwall)*f6-f6*(1.d0-fadc)

&)*(fldc-fhdc)

```

&!-----dc events where the alpha is not detected, and/or the
&!      alpha is below the ULD, and/or alpha out of range.
&      +f11*f22*(1.d0-fwall)*0.d0+
&      !0.d0 emphasizes that there can not be any Th-228 on wall
&      f13*f22*(1.d0-fwall)*(x*x2s)+
&      f15*f21*(1.d0-fwall)*0.36d0*(x*x4s)+
&      f11*f20*(1.d0-f32)+
&      !all Th-228 resides on the wire
&      (1.d0-x)*f13*f22*(1.d0-f14)+
&      f15*f21*(1.d0-f16)*0.36d0*((1.d0-x)**4.)
&!-----ja events where after the alpha decay has occurred
&!      the nucleus is in an excited state and decays by
&!      releasing a beta not a gamma which is consequently
&!      detected in the PCS as a jb event.
&      )*act+b_bg

```

```

      L(2)=f5*(dcwa*fwall*fwall+dcwi*f7)*
&(f1-f6)*(fldc)*act+dc_bg ! dc

```

```

      L(3)=(
& (jawa*fwall+jawi_wire)*faja
&!-----just alpha above ULD
&+(jbwa*fwall+jbwi*no_wire)*fhjb
&!-----just beta above ULD
&+f5*dcwi*f7*((1.d0-f1)*fhdc+(1.d0-f1)*fadc-
&(1.d0-f1)*fhdc*fadc)
&+f5*dcwa*fwall*((1.d0-f1)*fhdc+(1.d0-f1)*fadc-
&(1.d0-f1)*fhdc*fadc)
&!-----combination of seperation time less than tau_cut, or/and

```

```

&!      dc beta energy above ULD
&+f5*(dcwa*fwall+dcwi*f7)*fadc*(f1-f6)*(1.d0-fldc)
&!-----dc events with alpha above ULD but beta below LLD
&      )*act
&+a_bg

```

```

L(4)=(
&      f4*(jbwi+jbwa)*fhjb*eff_jb
&!-----jb events with beta above ULD
&      + f2*f5*dcwi*((1.d0-f1)*fhdc
&      +(1.d0-f1)*fadc*f7-(1.d0-f1)*fhdc*fadc*f7)
&      *eff_dc
&      + f2*f5*dcwa*((1.d0-f1)*fhdc
&      +(1.d0-f1)*fadc*fwall-(1.d0-f1)*fhdc*fadc*fwall)
&      *eff_dc
&!-----dc events with the seperation time less than tau_cut, or/and
&!      dc beta energy above ULD
&      )*act ! pmtspcja

```

```

L(5)=(
&      f4*(jbwi+jbwa)*(fljb-fhjb)*Eff_jb
&!-----true just beta events
&      + f2*f5*dcwi*((1.d0-f7)+f6+(1.d0-fadc)
&      - (1.d0-f7)*f6-f6*(1.d0-fadc)
&      )*(fldc-fhdc)*Eff_dc
&      + f2*f5*dcwa*((1.d0-fwall)+f6+(1.d0-fadc)
&      - (1.d0-fwall)*f6-f6*(1.d0-fadc)

```

```

&          )*(fldc-fhdc)*Eff_dc
&!-----dc events where the alpha is not detected, or the
&      alpha is below the ULD.
&      )*act
&      +cjb_bg    ! pmtspcjb

```

```

      L(6)=f2*f5*(dcwa*fwall+dcwi*f7)*(f1-f6)
&          *(fldc+fadc-fadc*fldc)*Eff_dc*act
& ! pmtspcdc

```

- * Definitions allowing the ratio's of various eqns to be fit as easy as
- * fitting the eqns themselves.

```

L(7)=L(1)+L(2)+L(3)
F(1)=L(1)
F(2)=L(2)
F(3)=L(3)
F(4)=L(4)
F(5)=L(5)
F(6)=L(6)
F(7)=L(7)

```

```

CHI = 0.0D0
  do i=1,7
    write (*,*),'er',1,' : ',er(i)
  enddo

```

- * CALCULATION OF THE CHISQUARED FUNCTION:


```
DO 100 I = 1,NDIM
    CHI = CHI + (F(I)-R(I))**2/ER(I)**2
    write (6,*),'EQN: ',i,'expt1: ',R(I),' fit: ',F(i),'chisq==>',
&(F(I)-R(I))**2/ER(I)**2
100  CONTINUE
```

```
FVAL = CHI
```

```
RETURN
```

```
END
```

```
*****
*****
*****
```

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END

0 5 | 0 6 | 9 | 6 |

FIN