Injection of a Uniform ^{24}Na Radioactive Source into the Sudbury Neutrino Observatory

by

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ABSTRACT

A solution of ^{24}Na was prepared, dissolved and uniformly mixed into the D_2O of the Sudbury Neutrino Observatory. This calibration will be used to understand the neutral current detector array response and to determine the array's overall efficiency. The source's activity was measured in four ways. In-situ using the photomultiplier array and the newly installed ^{3}He neutron detectors. Ex-situ using two ultra-pure germanium detectors. One located underground in the SNO laboratory, the other at Guelph University. The average strength from these measurements is 12.70 ± 0.49 MBq at the time of activation. The analysis shows that the source was uniformly distributed at the start of data taking and that the data is consistent with other neutron sources, and verified by Monte Carlo.

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Chapter 1. INTRODUCTION

1.1 SNO Overview

The Sudbury Neutrino Observatory is located near Sudbury, Ontario, Canada, two kilometers underground in INCO's Creighton mine. This location is ideal for an experiment which is sensitive to backgrounds from cosmic rays. The detector itself is a one-kilotonne ultra-pure heavy water Cerenkov light detector. The heavy water is contained in a 12 meter diameter spherical acrylic vessel (AV). This is surrounded by a 17.8 meter geodesic photomultiplier support structure (PSUP). This frame houses nearly 10 000 photomultiplier tubes. To shield the heavy water from external backgrounds and aid in support of the AV there is ultra-pure light water (H_2O) between the PSUP and the AV. On the outside of the PSUP the remainder of the cavity is filled with light water. This structure is shown in Figure 1.1

Since the early 1960's, experiments searching for solar neutrinos have been targeting the Sun's ^8B fusion reaction. This reaction produces electron neutrinos. Before SNO, there were four solar neutrino experiments: Homestake(1), Gallex(2), Sage(3), and Kamiokande(4). Although sensitive to different energies of neutrinos, all measured a substantial deficit in the flux of solar neutrinos. This was known as the *solar neutrino problem*(5). One of the possible explanations was that the electron neutrinos interact with the matter as they pass through and out of the Sun, causing

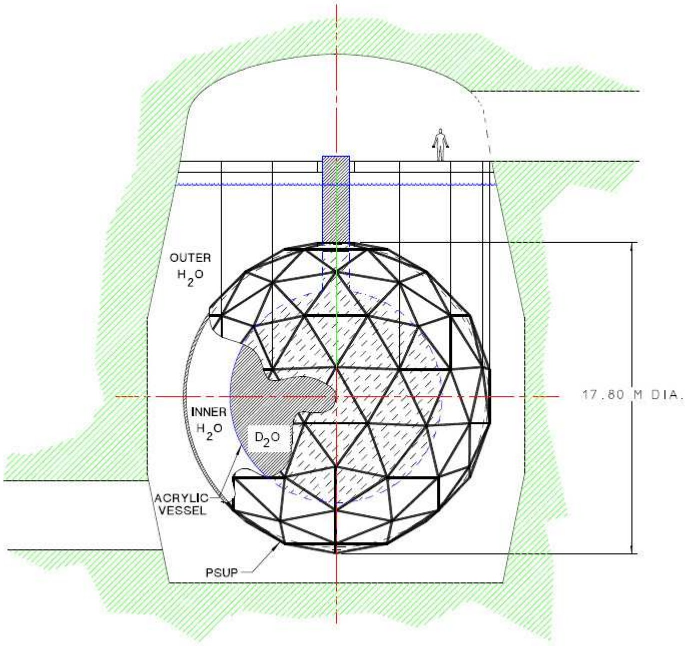

Figure 1.1: This is an artist representation of the SNO cavity containing the support structure and AV.

a change from the electron to the muon or tau neutrino. Previous experiments were sensitive only Homestake, gallex, Sage or predominately Kamiokande to the electron neutrino. SNO has the unique ability to detect all three neutrino flavours via the reactions:

$$\nu_e + d \rightarrow p + p + e^- \tag{1.1}$$

$$\nu_x + d \rightarrow p + n + \nu_x \tag{1.2}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \tag{1.3}$$

These equations describe the charged current (CC), neutral current (NC) with the deuteron and the μ_e and elastic scattering (ES) reactions respectively. The charged current reaction is only sensitive to the ν_e flavour, but the neutral current reaction is sensitive to any of the three flavours, ν_x, where x can be e, μ, or τ. All the experiments show a deficit of ν_e neutrinos. SNO's sensitivity to both NC and CC allowed SNO to distinguish an oscillation scenario ($\frac{\nu_e}{\nu_x} = \frac{1}{3}$) from a solar model scenario ($\frac{\nu_e}{\nu_x} = 1$). SNO solved the *solar neutrino problem* by showing that the rate of NC reaction events was predicted by the standard solar model(6), while the rate of charged current reaction events and elastic scattering events was consistent with oscillations in which two-thirds of the neutrinos at the Earth are ν_μ or ν_τ neutrino.

The SNO experiment was done in three phases. Each phase employed a different technique to detect neutrons. The first phase looked for neutron capture on the D_2O. The second phase involved the addition of NaCl salt. Chlorine has a larger cross section for neutron capture and thus improved the efficiency of the neutral current reactions. This increased the statistical precision. The third phase of SNO is discussed in the next section.

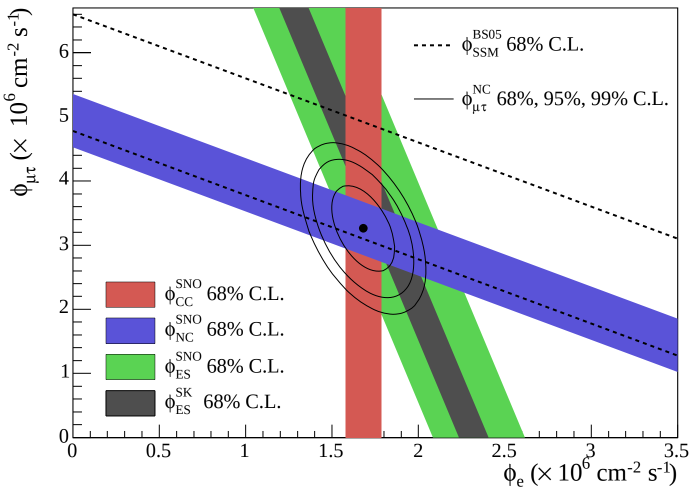

Figure 1.2: Flux of μ and τ neutrinos versus the flux of electron neutrinos. The NC, CC, and ES measurements can be seen in the bands. The dashed line represents the Standard Solar Model prediction for the flux from ^{8}B Solar neutrinos.(7)

The comparison of non-electron neutrino flux versus the electron neutrino flux based on phase two is shown in Figure 1.2. If we compare the rates of the NC and CC reactions, we get a ratio of:

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.358 \pm 0.021(stat)^{+0.028}_{-0.029}(syst)$$

This ratio shows that, if a detector were sensitive to only electron neutrinos (like the charged current reaction is), then there would be a deficit in the number of neutrinos seen. The full results of the second SNO phase are reported in (7).

1.2 Neutral Current Detector Array/Phase Three

The third and final phase of SNO was to install ^{3}He proportional neutron counters into the active volume. Thirty six of these detectors are in place as well as four ^{4}He counters. The purpose of the thirty six ^{3}He detectors is to detect neutrons from the NC interaction. The advantages are to increase the efficiency for the detection of the neutral current reaction, as compared to pure D_2O, and to allow event by event particle identification. The counters are referred to as neutral current detectors (NCDs). The NCDs are made up of strings of 3 to 4 individual counters. Each counter is an ultra-pure nickel tube with a 5.08 cm inner diameter. The tubes are strung with a 50 μm copper anode wire down the center, and are filled with a ^{3}He-CF_4 gas mix. The NCDs are 9 to 11 meters in length. They are arranged in a 1 meter rectangular grid inside the AV, as shown in Figure 1.3.

The ^{3}He nucleus has a large cross section to thermal neutrons (5330 barns), which allows the NCD to capture virtually all the neutrons which enter the tube.

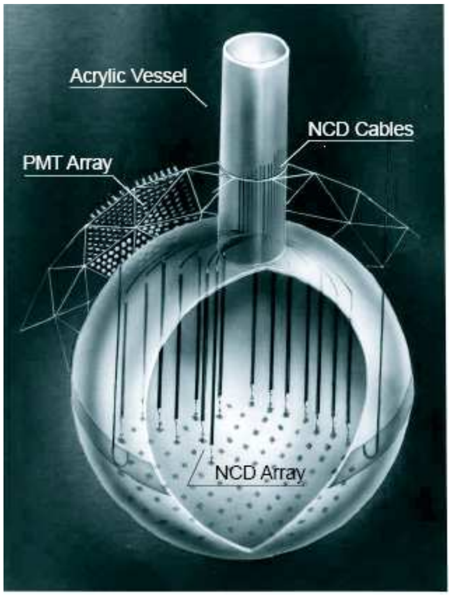

Figure 1.3: An artist's drawing of SNO and the NCD array.

The detection reaction is:

$$n +^3 He \rightarrow p + t \tag{1.4}$$

where p is a proton and t is a triton. The proton and triton are emitted anti-parallel and with kinetic energies of 573 and 191 keV respectively. If both the full energy of the proton and triton get deposited a total kinetic energy of 764 keV can be detected. If either or both hit the wall before depositing all their energy, less energy is seen. A typical spectrum is shown in Figure 1.4. The peak corresponds to events in which the full energy of the proton and triton is deposited in the gas. The 'hump' before the peak is due to 'space charge'. This effect is caused by the electrons created from the proton and triton ionizing the gas as they move through it. The electrons ionized most when they are close to the anode, so the density of the electrons there can be high. That density can decrease the electric field and therefore the gain of the detector. This shifts some energy out of the peak region, causing the 'hump'.

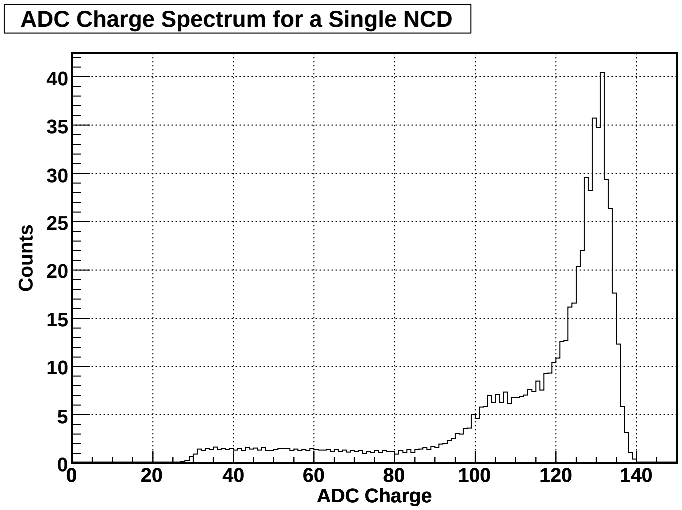

Figure 1.4: NCD ADC charge spectrum.

After the charge is deposited on the anode it then travels through a preamplifier (preamp), multiplexer, and into the analog to digital converter (ADC). This signal path can be seen in Figure 1.5. The preamplifier acquires the charge and linearly increases the amplitude of the pulse.

The output of the preamp is fed into a multiplexer, or MUX. The purpose of the MUX is to allow a single digitizer to be used to read out signals from several NCDs. An analog switch in the MUX is used to connect a given NCD preamplifier to a logarithmic amplifier which drives an oscilloscope. To perform this task, the NCD signal is split in three. One signal goes to a discriminator which fires if the amplitude of the pulse is greater than a threshold, which can be set in software. The output of this discriminator is used to set the analog switch in the MUX, and is also used to generate a trigger for the SNO data acquisition system. A second signal is delayed by 300 ns and then used as a signal for the logarithmic amplifier (logamp).

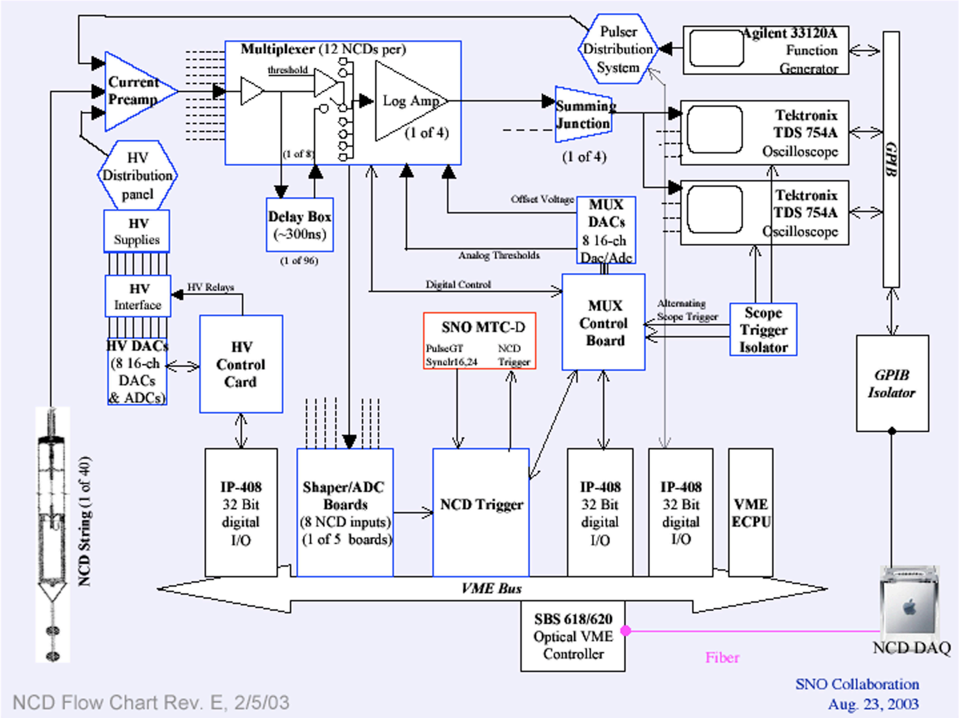

Figure 1.5: NCD Electronics Flowchart

The delay ensures that the analog switch is set before the signal arrives, and also allows the scope to digitize part of a pulse that precedes the trigger. The logamp allows a greater dynamic range for the oscilloscope. The third signal is used to drive the shaper board.

The pulse is sent to the shaper board where it is integrated. This integrated pulse then goes to the ADC where its peak value is measured and converted into a digital charge value. The integrated pulse is also passed through a discriminator, which can generate a system trigger. Shapers can be read out separately from the MUX. There are three possible event types: correlated events in which both a MUX fire and a shaper fire, uncorrelated MUX's in which a MUX fires but not a shaper and uncorrelated shapers. It is possible that when a MUX fires and the signal is ready to be connected to the scope, that the scope is still busy from a previous event. In this case, the system ignores the signal but reads out all the information from the event except the scope trace. Such an event is called a partial MUX scope event.

Chapter 2. MOTIVATION

The analysis of the neutral current phase of SNO requires that the ^{3}He proportional counters are very well understood and calibrated. The main strategy of neutron calibration is to use contained neutron sources and move them from point to point around the D_2O. A calibration source manipulator uses a set of motor controlled ropes to position sources throughout the D_2O volume. The manipulator is constrained to move in either the x-z or the y-z planes, and a typical calibration scan consists of many runs in which different points in these planes are sampled. Periodic scans allow us to check for changes in the detector response over time.

A Monte Carlo (MC) simulation of the detector, called the SNOMAN Monte Carlo Program, has been developed. This program includes the detailed geometry of the detector, and details of neutron and optical photon transport and detection. The Monte Carlo is used to extrapolate from a point calibration to a distributed source response. The accuracy of this MC needs to be checked. This thesis describes the design, deployment and analysis of a neutron source that could be uniformly distributed throughout the volume.

An example of the multi-position point source calibration of the NCD array can be seen in Figure 2.1, and an example of the uniformly distributed source can be seen in Figure 2.2. In these bubble plots, each bubble represents one of the NCDs, the area of the bubble indicates the number of counts in that counter. We can see that the uniform source samples the entire array homogeneously. Events from the distributed source can occur anywhere in the D_2O volume, just like the NC signal events. Thus, this is an ideal source to examine the response of the NCD array.

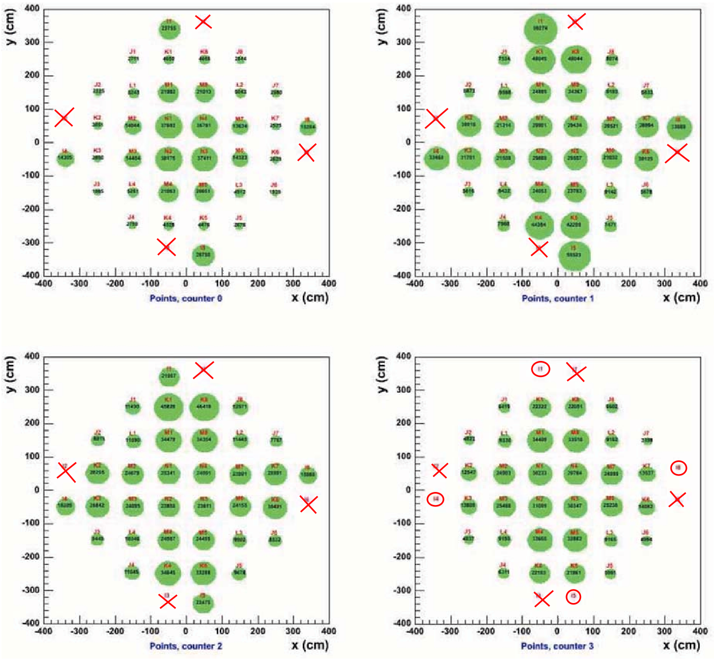

Figure 2.1: Bubble plot of a multi-point calibration scan using MC for the entire NCD array. Each plot represents a set single layer of counters, one for each string. The top left plot is the top counter on each string, then the top right is the top middle counter, then the bottom left is the bottom middle counter and the bottom right plot is the bottom counter on each string. It is possible to make these plots on a counter-by-counter basis for MC calculations, since the MC keeps track of the capture location for each neutron. The strings marked with an 'X' are the ^{4}He strings, which see no neutrons, the strings marked with a 'O' are the string which only have 3 counters.

The easiest way to get a uniform neutron source is to dissolve one into the D_2O. However, there are no known neutron sources that can be easily dissolved into the water. The next option was to find some isotope which decayed producing a gamma-ray with an energy greater than 2.2 MeV which would photo-disintegrate deuterons, d, in the D_2O into protons, p, and neutrons, n, through the reaction $\gamma + d \rightarrow p + n$.

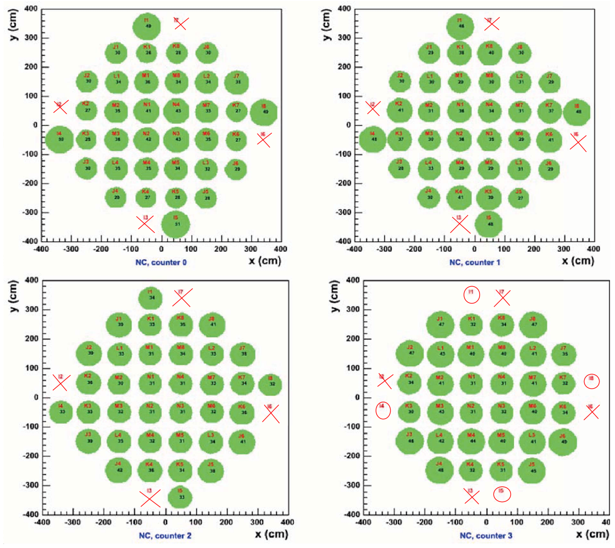

Figure 2.2: Bubble plot of Monte Carlo of a uniformly distributed calibration source in the active volume for the entire NCD array. Each plot represents a set single layer of counters, one for each string. The top left plot is the top counter on each string, then the top right is the top middle counter, then the bottom left is the bottom middle counter and the bottom right plot is the bottom counter on each string. It is possible to make these plots on a counter-by-counter basis for MC calculations, since the MC keeps track of the capture location for each neutron. The strings marked with an 'X' are the ^{4}He strings, which see no neutrons, the strings marked with a 'O' are the string which only have 3 counters.

This isotope needed to have a halflife short enough that it would not be a significant background for neutrino data taking for more than three weeks, but also allows enough time to mix the activity throughout the vessel, which is expected to take about 65 hours. An isotope with a halflife on the order of a day would meet the needs of this work.

The source also had to be pure so that other contaminants would not get introduced. It also could not effect other materials in SNO, such as acrylic or nickel. Sodium chloride (NaCl) salt, activated to ^{24}Na, was the most obvious choice because of the availability of purified NaCl brine from the second phase of operation. ^{24}Na has a 15 hour halflife which means that enough data could be collected in a weekend for the calibration and the radioactivity would be low enough to resume taking neutrino data one week after that. This week was not wasted, since it could easily be filled with other high rate calibrations which would not be adversely affected by small amounts of ^{24}Na and which were necessary. Purified NaCl was available to be used and the report of the known contaminants(8) was accessible and approved. In addition there was already approximately 1 kg present in the detector. Only 0.45 g was necessary to be added, which was a negligible change.

To transform NaCl or more specifically sodium into a neutron source, the standard ^{23}Na nucleus must be neutron activated to the radioactive ^{24}Na isotope. The activated NaCl with this isotope has about the same solubility properties in D_2O and is easy to make through neutron activation ($\sigma_\gamma = 0.53$ barn) and has a half life of 14.96 hours. It decays through $^-\beta$ decay to produce a 1.368 MeV and a 2.754 MeV gamma ray, as seen in the decay scheme shown in Figure 2.3. One in every 380 2.7

MeV gamma rays will photo-disintegrate a deuteron in SNO producing a neutron.

Neutron activation of NaCl also creates chlorine isotopes ^{36}Cl and ^{38}Cl, that have halflives of 3×10^5 years and 37 minutes respectively. These could be a problem, but fortunately, ^{36}Cl does not emit gamma-rays and ^{38}Cl's activity vanishes in a few hours after activation. There was also a concern that other long-lived activities may be introduced into the detector. This could be U or Th contaminants in the solution or other sources created through activation. These risks are looked at in more detail in Chapter 5.

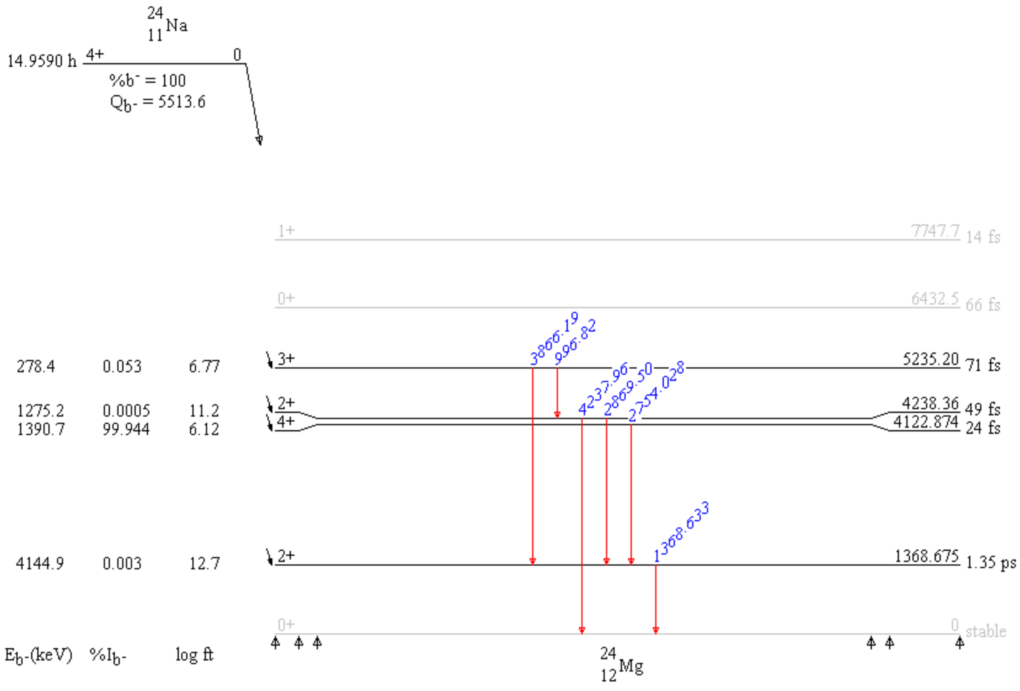

Figure 2.3: Decay scheme of ^{24}Na.(9)

2.1 Experiment Overview

The remainder of the thesis will detail the development, deployment and data analysis for this source. The general procedure that was developed to produce and deploy the source is outlined below. The details of the procedure can be found in Chapter 4.:

- Start with about 3.75 ml of 10% NaCl brine obtained from the SNO water group. Package into three 1.25 ml vials at Queen's. With each brine sample include a sample of pure D_2O to check for contaminants from the reactor.
- Activate the ^{23}Na to ^{24}Na at the SLOWPOKE-2 reactor(10), located at the Royal Military Collage (RMC), located in Kingston near Queen's University.
- Transport activated samples back to Queen's.
- Combine samples into new vial and measure their activity with a germanium detector.
- Transport sample to Sudbury, and then to the underground SNO Facility.
- Dilute sample into 2 l of degassed pure D_2O.
- Deploy the ^{252}Cf source (a neutron source of known strength) in the center of the D_2O for three hours. A comparison of this source to a very similar source made with a sample of the ^{24}Na allows us to measure the ^{24}Na source strength.
- Remove three samples for measurement:

  - About 30 ml for the underground germanium detector.
  - About 30 ml for the germanium detector at Guelph University
  - About 10 ml for a SNO-based measurement.

- The 10 ml sample is placed into a delrin container and deployed into the center of the D_2O volume and collect data for 24 hours
- Inject nearly 1 l of diluted brine into the D_2O.
- Collect data for 3-4 days.

Chapter 3. DESIGN

3.1 Strength Determination

The goal of the calibration was to determine the efficiency of the NCD array to a precision of at least 1%. For that statistical precision we needed to detect at least 10 000 neutrons with the NCD array. To do this we determined that at the start of data taking we would need a minimum activity of 225 Bq, if we were to take data for 65 hours.

$$A(t) = -\frac{dN}{dt} \tag{3.1}$$

$$N(t) = N_0 e^{-\lambda t} \tag{3.2}$$

in the above calculation $\lambda = \frac{ln2}{t_{\frac{1}{2}}} = 0.04633h^{-1}$. $t_{\frac{1}{2}}$ is the halflife as given in Figure 2.3 as 14.96 hours. $N(t)$ is the number of ^{24}Na nuclei at time t, and N_0 is the number of ^{24}Na nuclei at $t = 0$. $A(t)$ is the activity at time t, and A_0 is the activity at $t = 0$.

Putting equation 3.2 into 3.1, we get:

$$A(t) = -\lambda N_0 e^{-\lambda t}$$

at $t = 0$,

$$A_0 = \lambda N_0 \tag{3.3}$$

The integrated number of ^{24}Na nuclei that have undergone $^{-}\beta$ decay over the time interval t is given by:

$$N = N_0 - N_0 e^{-\lambda t}$$

Giving N_0 as:

$$N_0 = \frac{N}{1 - e^{-\lambda t}} \tag{3.4}$$

Combining equations 3.3 and 3.4 we get:

$$A_0 = \frac{\lambda N}{1 - e^{-\lambda t}}$$

and using $N = 10000 \times 380$ and $t = 65$ hours, we need an injected activity of:

$$A_0 = 51Bq$$

From Monte Carlo studies the NCD array is expected to have about a 25% efficiency, meaning our injected activity will have to be:

$$A_0 \approx 200Bq$$

This calculation is shown starting from the standard equation for radioactive decay (equation 3.1). The method to get the most precise source strength will be discussed more in section 3.6.2 and 4.7.2.

Since it takes nine days between the production of the source at the RMC Slowpoke reactor and the time that the source has been injected and mixed into the detector, we need to include an additional factor in the source strength to compensate for the radioactive decay. This means we need an activated strength of 5 MBq at the time of activation. To be safe this was multiplied by 3. This allowed us to be conservative and, in the case it was unnecessary would only add 30 hours of deadtime after the experiment was finished.

3.1.1 ^{24}Na Source Strength Measurements at Queen's

The first attempt to activate and measure ^{24}Na was done at Queen's. Two samples of NaCl heavy water brine were obtained from SNO's water group. These samples were activated at Queen's using a 0.5 Ci RaBe source and the gamma rays were observed using a NaI gamma-ray detector.

This NaI crystal is in the shape of an annulus 33 cm in length and with a diameter of 32 cm. It has an open cylinder along the center z-axis, 9 cm in radius. The NaI scintillator produces about 30,000 photons per 1 MeV of energy it absorbs. The annulus was used to ensure a high efficiency (since it covers a large area, a solid angle of nearly 4π) for detecting the gamma-rays, however the energy resolution was very poor. This poor resolution made it nearly impossible to distinguish between close energy peaks, such as the 1173 and 1333 keV lines of the common calibration source ^{60}Co.

To get better resolution we turned to germanium detectors for improved energy resolution but lower efficiency. A counter was necessary to quickly determine the amount of activity we had created. A 3 inch germanium detector was available in the teaching labs at Queen's and was used to obtain approximate source strengths shortly after activation.

3.1.2 Neutron Sources for Activation

From the measurements done at Queen's it was determined that the 0.5 Ci neutron source could not provide sufficient neutron flux to activate the sodium to the desired activity. RMC was then contacted and permission was obtained to use their SLOWPOKE-2 research nuclear reactor to activate the D_2O brine. At half power they are able to produce a flux of 5×10^{11} neutrons/cm^2/sec at one of the inner sites. With this flux we calculated that we would need to activate our samples for 25 minutes.

3.2 Mixing in the D_2O

A major design criterion of the experiment was to decide how to mix the source and to ensure that the source was indeed uniformly distributed within the D_2O. We have no exact model of how the D_2O circulates inside the AV. However, the circulation was observed in the second (salt) phase after two calibrations. A high rate neutron source (1000 n/s) was used to create ^{24}Na in the D_2O, and a ^{222}Rn sample was injected into the water. Following each, the motion of the water was carefully observed.

During these measurements we circulated the D_2O from the bottom of the vessel and returned it to the top. We saw that the activity quickly mixed uniformly throughout the top 400 m^3 of the D_2O volume. Thus we decided that the best scheme was to inject ^{24}Na at multiple points along the Z-axis with the majority being added to the bottom 90 m^3. Based on our previous trials, this would produce a uniformly distributed source in less than 65 hours.(11)

3.3 Impact of Injection on the SNO Electronics and Data Acquisition System

At the time of injection the activity of the ^{24}Na was 23.2 kBq. During the 65 hours of mixing, this rate would drop to 1.2 kBq. If we used normal data acquisition (DAQ) settings, this rate would swamp the SNO photomultiplier tube (PMT) system, which is sensitive to the 2.754 and 1.368 MeV gamma-rays.

The SNO data acquisition system limits the trigger rate of the PMT array to be less than $\sim$300 Hz. Injecting 23.2 kBq of ^{24}Na caused a trigger rate greater than 1kHz. Normally SNO is triggered if 15 or more PMTs sense photons within a 100 ns time window. To satisfy these trigger rate constraints we raised the number to 33 and slowly returned it to 15, as the ^{24}Na decayed.

3.4 2.5 litre Mixing Vessel

Once the ^{24}Na brine is underground it must be prepared for injection. A canister was designed to meet these needs. This canister is a cylindrical acrylic vessel which can hold up to 2.5 l of liquid, as shown in Figure 3.1. This canister was designed to maintain the purity of the ^{24}Na brine sample. It was held under pressure with nitrogen gas to reduce exposure to the contaminants that were present in the mine air environment in which the mixing took place. It had four air tight valves that had swagelok couplings. In the center of the top there was a stainless steel rod which was sealed with O-rings around the sides. Inside the vessel this rod was connected to a stainless steel paddle which was used to mix the liquid in the volume. The rod was connected to a hand drill which spun the paddle to mix the solution.

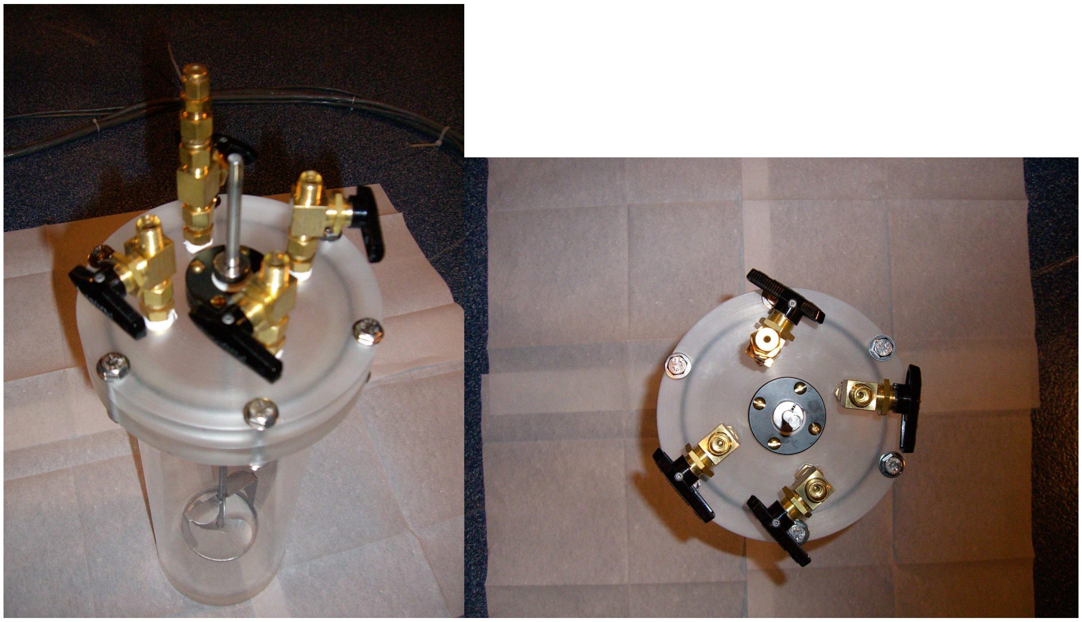

Figure 3.1: 2.5 l canister used to dilute activated ^{24}Na sample. A full view on the left, and a top view on the right. The drill was attached to the middle rod on top.

3.5 Injection Device

The injection device, shown in Figure 3.2 was the same apparatus used for the ^{222}Rn spike described in (12). The brine is injected by pumping it from the mixing chamber through a 0.6 mm diameter Teflon tube. This tube runs through the centre of a ultra-pure silicon cable, called an "umbilical", that runs from the 2.5 liter can to the injection device. At the top of the injection device a Teflon tube is connected to a length of stainless steel tubing that is wrapped around a stainless can that is part of the manipulator system.

Attached to the end of the injector there is a stainless steel plate which was in place to cause the injected brine to diffuse into the D_2O. To test the system the injector was set up in a tank of H_2O at Queen's. A bottle was filled with 10% NaCl in an H_2O solution. This brine also had red food colouring added so that its motion could be seen when it was pumped into a tank of water.

The tests showed us that the injected solution would tend to sink without mixing. This is not unexpected since the brine has a very different density from water. These tests showed that we would need to dilute the brine as much as possible before injection, and led to the choice of 2.5 l mixing volume. In addition, many different attachments were tried to reduce the problem. When a plate was a distance of 13 mm from the injector tip the most mixing was seen. The brine seemed to spread out and diffuse into the water. This distance was then used for the ^{24}Na injection into the D_2O.

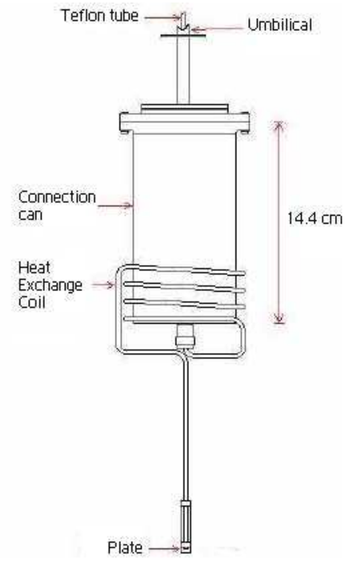

Figure 3.2: ^{24}Na Injection Device.(12)

3.6 Apparatus for Measurements of the Sample Activity

3.6.1 10 ml Central Run Delrin Can

The strength of the ^{24}Na diluted solution that was injected into the active volume needed to be determined. One measurement of the ^{24}Na source strength uses SNO to measure the neutron rate, both with a ^{252}Cf source and with a sample of the ^{24}Na source. To make this comparison as accurately as possible, we wanted to make the ^{24}Na sample similar in geometry and composition to the ^{252}Cf source. The ^{252}Cf source consists of a right cylinder made from acrylic, with diameter 1.125 inches and height 1.625 inches, as shown in Figure 3.3. We made a delrin can as shown in Figure 3.4.

A correction factor accounts for the different geometry variations between the sealed ^{24}Na source and the ^{252}Cf source. The correction factor was 1.0392 ± 0.0075. This was determined by using the SNO Monte Carlo. A 10 ml sample of the diluted ^{24}Na brine was placed in the delrin can and sealed. This can was then placed in a second delrin can. This created a double seal so that there was confidence of no leakage of the radioactive solution into the D_2O which would confuse the measurement.

3.6.2 Underground Germanium Detector

A germanium detector for counting samples at SNO is located just outside the SNO underground control room. This detector is complete with lead shielding and an N_2 gas flush around the sample. The sample had to be placed in a *Marinelli beaker*(13), which is a seamless 3 mm thick, polypropylene container designed to fit over the endcap of the germanium detector. The Marinelli beaker, GA-MA Associates, Inc., model 132G-E, is shown in Figure 3.5. It has a tight-fitting polyethylene snap-on cover. Using a Marinelli beaker allows the germanium crystal to be covered on all sides of the cylinder, except the bottom.

Much effort was put into making sure the sample had the same geometry as the

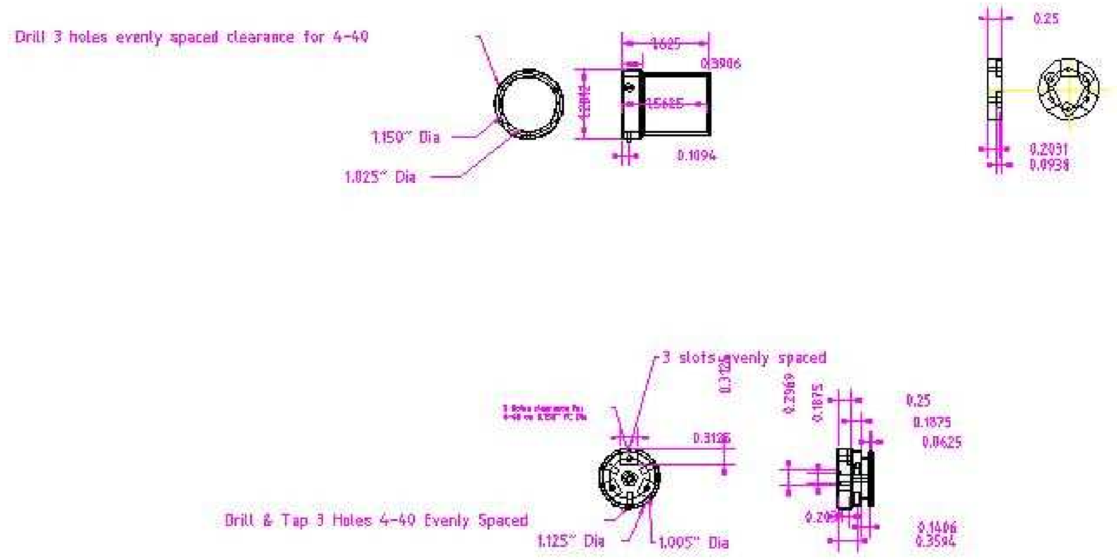

Figure 3.3: Drawing of ^{252}Cf source.

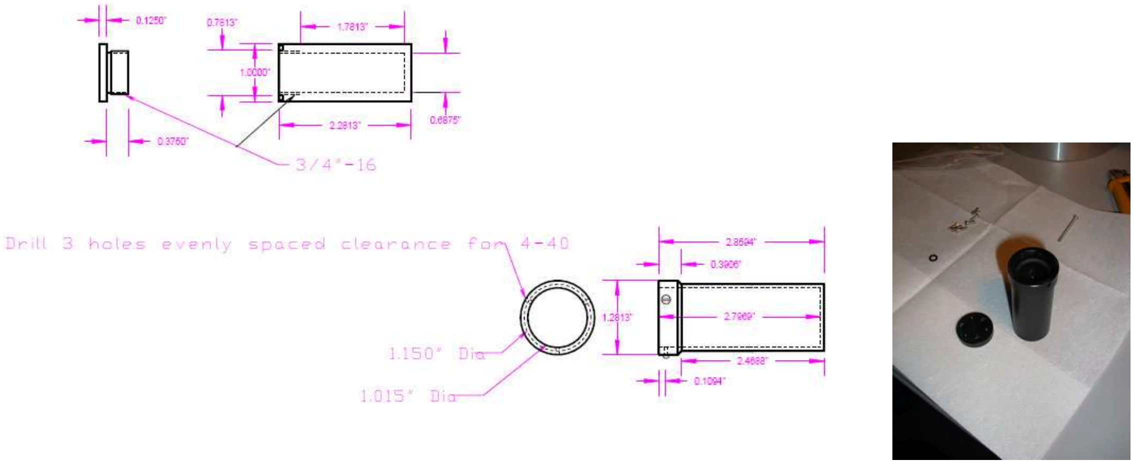

Figure 3.4: Delrin canister deployed into the center of the AV. Left: drawing of the inner and outer cans; right: photo with the inner can inside of the outer can.

Figure 3.5: Marinelli beaker used to measure ^{24}Na source with the underground germanium detector.

calibration source, which was a distributed source of ^{65}Zn, ^{88}Y, ^{85}Sr, ^{137}Cs, ^{54}Mn, ^{133}Ba, ^{57}Co, ^{139}Ce in a polymer, inside a Marinelli Beaker. The 30 ml sample that we counted with this detector was placed into the Marinelli beaker, then had 800 ml of D_2O added, so the beaker had the same active volume as the calibration source.

3.6.3 Guelph Germanium Detector

A germanium detector located at Guelph University was also used(14). All measurements taken at Guelph were carried out by Pillalamarr Jagam, from the University of Guelph. This detector was custom built to search for the zero neutrino double-beta decay of ^{76}Ge. The natural germanium crystal was 7.6 cm in diameter and 7.6 cm thick mounted on the end of a one meter long cold finger.

The germanium detector was set up with a 4π shield to eliminate the line-of-sight paths of background gammas. The shielding was made up of 6 mm thick mercury on all sides, including the endcaps. The mercury was held in a cylindrical acrylic container with a removable disk at the top so that the sample could be inserted in the counting cavity. The mercury was surrounded by 15 cm of low activity level lead. The lead on the top could be removed to allow access to the shielded cavity.

The NIM standard electronics were set up to get approximately 1 keV per channel with 4095 channel 50 MHz external ADC coupled to a PC based counting system. The spectra were saved every four hours for analysis offline.

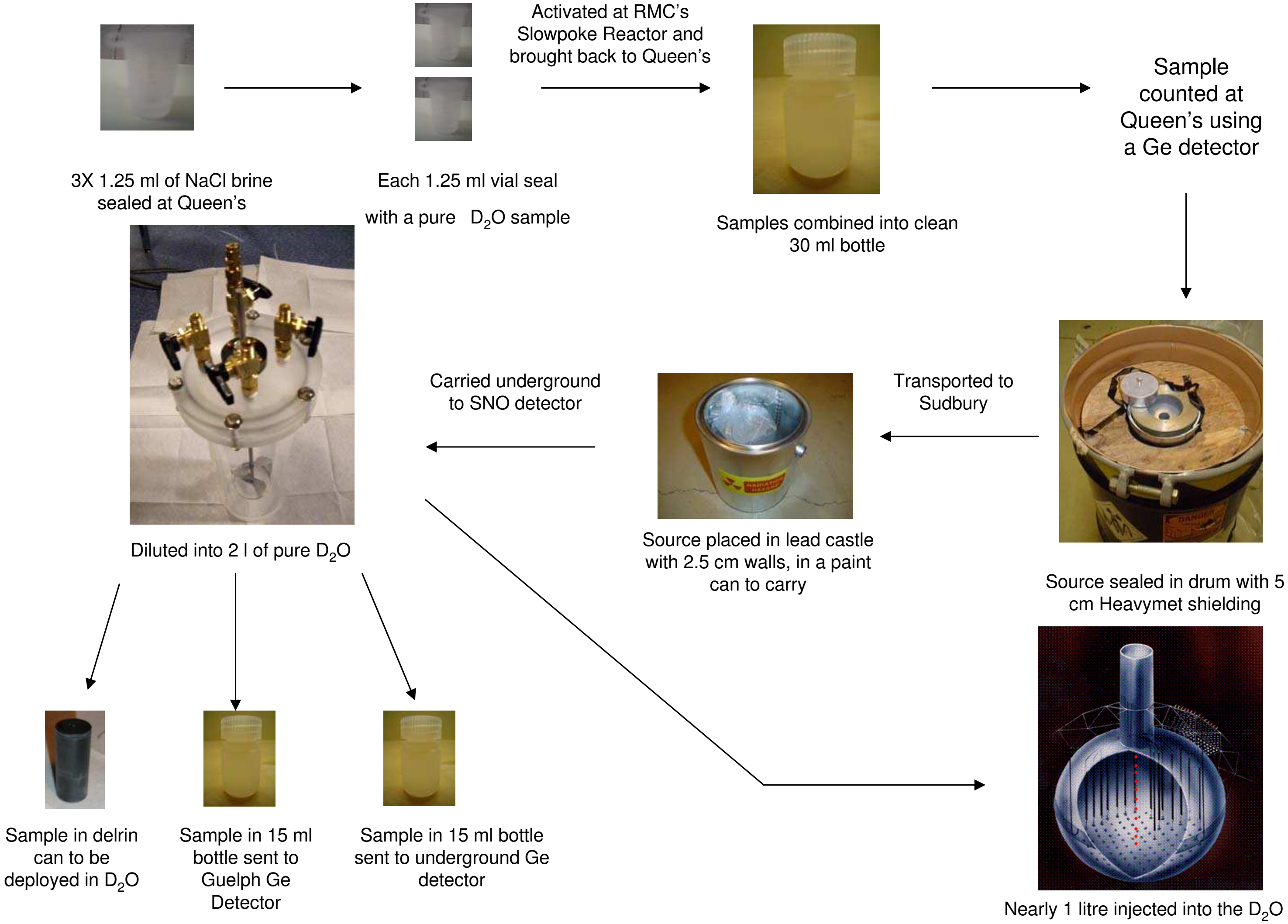

Figure 3.6: Path of the ^{24}Na travelled from start of experiment to end.

Chapter 4. PROCEDURE

4.1 Schedule

The process of activation, transportation, measurement and injection had many components and took considerable coordination between many people at different institutions. To make sure we had a good understanding of what was needed and the process that was to take place we planned a trial run in which the entire procedure up to the injection into the heavy water was to be performed. The first preparation run showed several issues that needed to be resolve. There were people that were not notified, or not notified soon enough and equipment that was needed, but not ready or in some cases not known about. We made these corrections and completed a second preparation run. Finally, the actual injection was performed. There are a large number of detailed steps, and the procedure should be documented for the future, I have incorporated the detailed schedule and procedures into a set of tables. Tables 4.1-4.3 detail the schedules for the threes runs.

July 28, 2005	• Activated ^{23}Na to ^{24}Na at RMC, brought it back to Queen's.
August 2, 2005	• Drove ^{24}Na to Sudbury.
August 3, 2005	• Transported sample underground. • Cleaned DCR. • Inspected and tested all injection equipment. • Diluted brine and took two samples, one for Queen's, the other was sent to Guelph and measured using a germanium detector.

Table 4.1: Schedule for first preparation run

September 7, 2005	• Activated ^{23}Na to ^{24}Na at RMC, brought it back to Queen's.
September 11, 2005	• Drove ^{24}Na sample to Sudbury.
September 12, 2005	• Brought ^{24}Na sample underground. • Diluted brine into about 2 l of D_2O. • Took three samples; One to underground germanium detector, sent one to the Guelph germanium detector, put one in delrin can to be deployed in SNO. • Deployed double sealed delrin can containing ^{24}Na brine into SNO. • Placed sample in underground germanium detector.
September 13, 2005	• Removed delrin can from SNO, checked for leakage. • Observed preliminary results from germanium detector, checked for radioactive contaminants in sample.

Table 4.2: Schedule for second preparation run

September 28, 2005	• Activated ^{23}Na to ^{24}Na at RMC, it was then brought back to Queen's.
September 29, 2005	• Drove the ^{24}Na sample to Sudbury.
September 30, 2005	• Transported ^{24}Na sample underground. • The DCR was cleaned, in preparation for work with the open source. • Diluted the 3.6 g brine with 1516.7 g D_2O. • Took a 30.62 g sample to the underground germanium detector. • Sent a 30.44 g sample to Guelph to be measured with the germanium detector. • Put a 10.36 g sample in the delrin can for SNO. • Start a 3h38m long ^{252}Cf central source run.
October 3, 2005	• Deployed delrin can in center of SNO. • Checked preliminary underground germanium detector results. Radon was detected. • Modified the source packaging to contain less mine air. This was used to determine if the source of the radon was the air or in the sample.
October 4, 2005	• Check underground germanium detector results. They verified that radon was in the air. • Removed delrin can from SNO after running for 19h40m. • Injected 968.7 g of diluted brine in the D_2O. • Took data for 65 hours.

Table 4.3: Schedule for ^{24}Na Injection.

4.2 Activation

The activation took place at the RMC SLOWPOKE-2 reactor. To use the Slowpoke reactor we were restricted to use polyethylene 1.25 ml bottles, placed inside 7 ml polyethylene bottles which held two 1.25 ml bottles, one on top of the other.

The procedure to fill the bottle is:

- **Purpose:** To fill the four 1.25 ml vials with brine and four 1.25 ml vials with pure D_2O. One of each will be put into a 7 ml vial, so that there are four 7 ml vials each with a brine (bottom) and pure D_2O sample (top).
- **Location:** Queen's clean room
- **Apparatus:**
  - Ultrasonic cleaner.
  - 12 1.25 ml vials, 7 7ml vials.
  - 5 10 ml pipettes.
  - Soldering iron.
  - 1 bottle of methanol.
  - 1 box of gloves.
  - Scale accurate to 0.01 g.
  - Permanent marker.
  - 1 scalpel.
  - 30 ml bottle of 10% NaCl brine.

  - 30 ml bottle of pure D_2O.

- **Number of People:** Two.

1. Obtain the 10% NaCl brine and pure D_2O from the water group in Sudbury (they can ship the bottle to Queen's using a courier).
2. Obtain 12 1.25 ml and 7 7 ml bottle from RMC.
3. Collect 5 10 ml pipettes.
4. Obtain a new soldering iron.
5. Move bottles, pipettes and soldering iron into a clean room.
6. Ultrasonically clean items from steps 2 and 3. Use about 100 ml of cleaner per litre of distilled water. Use the "heat on" mode on the cleaner.
7. Rinse bottles with methanol.
8. Leave to dry in a laminar flow hood.
9. Put on gloves.
10. Person A obtains the bottles and pipettes from the flow hood and places them on the work bench.
11. Person A selects one 1.25 ml vial and weighs it on the scale. This weight is recorded in a logbook.

12. Person B uses a pipette labelled 'D_2O' to move the pure D_2O sample from the 30 ml bottle into the vial, or when moving the brine use the pipette labelled 'brine'. It is recommended by the RMC technicians to fill the vial with no more than 1 ml. This is to reduce the chance of moisture getting into the heat seal and causing a leak.

13. Person B then records the weight of the full vial.

14. Person A then closes the lid and removes the sample from the scale and labels the vial with the date and contents, writing directly on the vial with the permanent marker. The sample is placed on the work bench.

15. Repeat steps 11 through 14 for each vial.

16. Person B carries out all subsequent steps. Person A can leave.

17. Each vial has a hinge which attaches the lid to the vial, it also has a flap to easily open the vial. Remove all of the hinges and flaps with a clean scalpel (this must be done to allow the 1.25 ml vial fit into the 7 ml vial).

18. Use the soldering iron to seal the 1.25 ml vial. **NOTE:** Before sealing can be done, RMC technicians must be present and give approval of technique before they will allow externally (of RMC) sealed vials to be used in their reactor. To seal the vials (1.25 ml and 7 ml) with the soldering iron:

    (a) Preheat the soldering iron.

    (b) Hold soldering iron in one hand and vial in the other.

   (c) Place seam of lid and cap to iron and slowly rotate the vial (about 1 rotation in 10-15 seconds).

   (d) Visually inspect seal, looking for sections that may not be heat sealed.

   (e) Wrap seal in tissue (*Kim Wipe*), shake vial.

   (f) Check tissue for moisture.

19. Repeat step 17 and 18 for all 1.25 ml vial.

20. Put a 1.25 ml vial containing brine in the 7 ml vial then a 1.25 ml vial containing pure D_2O on top. This is because the SLOWPOKE-2 reactor has the most uniform flux along the horizontal plane, and the flux varies rapidly vertically. Four samples were activated simultaneously, and having all the brine in the bottom allowed them to be exposed to a similar neutron flux from the SLOWPOKE-2 reactor.

21. Repeat step 20 until all four 7 ml vials have two samples each (one brine, one pure D_2O).

22. Trim the hinges and flaps on the 7 ml vial as well, to allow the vial to travel smoothly though RMC's "rabbit" system. This system allows the RMC technicians to send the vials, using compressed air, through a pipe system to put the vial near the reactor, and then retrieve them from their control room located away from the core.

The samples were brought to RMC at 08:00 on a Wednesday and activated for 25 minutes. This allows us to follow the schedule in Section 4.1 in order to get them underground and prepared before the injection. The samples were aged for four hours after the activation took place to allow the activated chlorine to decay before handling. Regulations require that samples had to be transported by personnel who are licensed to transport and handle dangerous goods. To keep below the limits that would have required any additional licenses, each 7 ml bottle (which contained one 1.25 ml sample of activated brine) had to be transported individually from RMC to Queen's.

The sample was transported in a *heavymet* (90% W, 6% Ni, 4% Cu, density $\rho =$ 16.9 g/cm^3) castle with 2 inch thick walls. Heavymet is much denser then lead (ρ = 11.34 g/cm^3) which means our castle could have thinner walls to give the same shielding against the radioactivity. This castle was placed in a large barrel, shown in Figure 4.1.

The procedure to transport the samples from RMC to Queen's is:

- **Apparatus:**
  - Heavymet container (in barrel in Figure 4.1).
  - Dolly.
  - Heavy duty straps.
  - Geiger counter.
- **Number of People:** Two.

1. Strap barrel containing the heavymet castle onto the dolly.

2. Lift the barrel and dolly into the back of a station wagon. Two people are needed, since the barrel is very heavy.
3. Drive to RMC.
4. Both people lift barrel (attached to dolly) out of the car.
5. Take the barrel to the RMC control room. In the room go to the lead box were the sources are being stored.
6. Undo the bolt and remove the rim holding the lid on. Remove the lid and open the heavymet castle.
7. Open RMC's lead box
8. Remove the sample from the RMC lead box with tongs and quickly place it in the heavymet container.
9. Close the heavymet castle and the lead box.
10. Wrap the seal around the rim.
11. Insert the bolt and tighten by hand.
12. Verify the activity on the outside of the barrel is below the legal limit using the geiger counter. The legal limit is 15 mSv/h at a distance of 15 cm from the surface.
13. Bring the barrel back to the car.
14. Both people lift the barrel into the car.

15. Drive the sample back to Queen's.
16. Both people unload the barrel. Wheel it into the radioactive vault.
17. Open the bolt, undo the rim and open the lid of the barrel.
18. Take the lid off the heavymet castle.
19. Use to tongs to remove the sample, put it in a lead box.
20. Steps 2 to 19 were repeated for all activated samples.

Figure 4.1: Barrel used to transport the ^{24}Na source from Queen's to Sudbury. Contained a heavymet castle which had 2 inch thick walls.

4.3 Preparation of Sample

Before the samples could be used the they had to be transferred into new ultrasonically cleaned vials. This was to ensure that there were no contaminants on the outside of the vial from RMC. It would be possible for contamination from activated dust or cross contamination from another sample at RMC to come in contact with the vial.

A safe work area at Queen's was built in order to transfer the source from the RMC vials to the new vials. An 'L' shaped lead work area was created with barrier that was 2 inches thick on the bottom and had a 2 inch thick wall between the worker and the source.

- **Purpose:** To transfer the source from the vials used at RMC to clean vials, in a clean bag to be brought to SNO.
- **Location:** Room attached to radioactive vault at Queen's.
- **Apparatus:**
  - Sources from RMC.
  - 2 clean scalpels.
  - 2 ultrasonically cleaned pipettes.
  - Two lead jars to contain samples.
  - Re-sealable plastic bags.
  - Permanent marker.
- **Number of People:** One.

1. Obtain two scalpels. One for opening the outer 7 ml bottle, label this "outer", and one for opening the D_2O and brine samples, label this "inner".

2. Obtain two ultrasonically cleaned pipettes. Label one pipette "D_2O", for the D_2O and the other label "brine" for the brine.
3. Put on gloves.
4. Gloves should be changed before handling the clean pipette or the clean vial if they have come into contact with any potentially contaminated surfaces (RMC vials, lead, scalpels, etc.).
5. Open the lead box containing the 7 ml vial brought from RMC.
6. Bring a 7 ml vial to the work area.
7. Place the vial in a lead jar so that just the top of the bottle is showing. This reduces the exposure to radiation as much as possible.
8. Use the "outer" scalpel to slice the top off.
9. Dump the top inner vial (D_2O) into a re-sealable bag labelled "D_2O." Then dump the bottom inner vial in to a re-sealable bag labelled "brine." Treat the inside of the bag as clean, and the outside as dirty.
10. Seal the bags.
11. Separate the two inner vials. Check each with a Geiger counter to double check the D_2O has no activity and the brine does. At this point the activity will be very high so it will be obvious when the counter is near an activated source.
12. Place the bags containing the brine in a lead box.

13. Repeat steps 4 through 12 for all outer vials.

14. Put all empty vials in a re-sealable plastic bag and label with date.

The next step involved transferring the pure D_2O out of the vials that had been activated into new clean vials. The procedure is as follows:

- **Location:** Room attached to radioactive vault at Queen's.
- **Apparatus:**
  - 1.25 ml vials of brine and pure D_2O in sealed bags.
  - Re-sealable plastic bags.
  - Permanent marker.
  - 4 ultrasonically cleaned 15 ml screw top bottles (Figure 4.2). 15 ml was the smallest bottle available with a screw top lid. If a smaller bottle were available, it would be preferred.
  - Bags made with plastic that can be air tight sealed using a heat sealer. This can create a seam which melts two layers of plastic together. Obtain or make 3 bags which fit snugly around the 15 ml bottles.
  - Acrylic plates, cleaned with *alconox*, with holes drilled into it to hold 1.25 ml vials.
- **Number of People:** One.

1. Put on gloves.

2. Get bag with a pure D_2O vial, bring to work area.
3. Open one of the 15 ml screw top bottles.
4. Open bag.
5. Place a 1.25 ml vial filled with D_2O in the acrylic plate so that just its lid is showing.
6. Slice the lid slowly off with the "inner" scalpel.
7. Use the "D_2O" pipette to transfer the water into a 15 ml screw top vial.
8. Repeat steps 2 to 7 for all D_2O samples, combining into the same 15 ml bottle, so that at the end there will only be one bottle containing pure D_2O.
9. Close the lid on the new bottle and label with the date and "D_2O".
10. Change gloves.
11. Open two of the remaining three 15 ml screw top bottles.
12. Get bag with a brine vial, bring to work area.
13. Open bag.
14. Place a 1.25 ml vial filled with brine in the acrylic plate so that just its lid is showing.
15. Use "brine" pipette to place sample into one of the two remaining screw top 15 ml bottles.

16. Repeat steps 10 through 15 for three of the four brine samples. Divide it up with two samples in one bottle, and one sample in the other.
17. Close the screw top bottles. Label with the date and as ”brine.”
18. Put each of these 15 ml bottles into an air tight bag.
19. Put a second air tight bag around each of the 15 ml bottles containing a brine sample.
20. Put all samples in a lead box in the radioactive vault.
21. Change gloves.
22. Open last 15 ml bottle.
23. Repeat steps 12 through 15 for last brine sample into last 15 ml bottle.
24. Close the screw top bottle. Label with the date and as ”Sample for counting at Queen’s.”

The samples were divided up so they could be easily transported underground. If they were all combined into a single container there was a danger of being too radioactive to carry in a small lead box. The last sample was left at Queen’s to be measured using a germanium detector to get an approximate strength to ensure that there would be enough activity when the experiment took place at the SNO facility.

Figure 4.2: Screw top bottle that the radioactive ^{24}Na sample was transported from Kingston to Sudbury.

4.4 Transportation to Site and Underground

The combined source strength two days after activation was about 4.5 MBq. This was below the legal limit of 15 MBq which allowed the sample to be taken from Queen's to Sudbury in a personal vehicle with no addition of placards or paperwork.

To handle sources in the SNO facility above, or below ground, you must be on the approved list, which requires a radiation safety course and approval from the radiation safety officer at SNO. To transport a radioactive source which is above the exemption quantity requires a license to transport and handle dangerous goods.

To get the sample to Sudbury and underground:

- **Purpose:** To transport all necessary materials and sources to SNO site in Sudbury.
- **Location:** Queen's to SNO site.
- **Apparatus:**
  - 2 double sealed air tight bags containing sources.
  - 2 lead castles with 1 inch thick walls.

  - 2 paint cans which can each hold one lead castle.
  - 2 scales, one accurate to 0.1 g (4 kg max.), one accurate to 0.01 g.
  - 12 inch needle.
  - 2.5 litre mixing vessel.
  - Extra teflon tubing.
  - Injection device.
  - Delrin can.
  - 3 ultrasonically cleaned, empty 30 ml screw top bottles.

- **Number of People:** One to travel to Sudbury, two to get sources from SNO site surface to the underground facility.

1. Put both 15 ml screw top bottles which are each double bagged into the heavymet castle in the barrel.
2. Tape down lid of heavymet castle to ensure the lid is secure.
3. Close barrel, wrap rim around and hand tighten bolt.
4. Strap barrel into a car.
5. Load all apparatus into car.
6. Notify the radiation officer at SNO when the source is leaving Queen's.
7. Drive the car to Sudbury.
8. Notify radiation officer at SNO site when the source arrives at SNO site.

9. At site open the barrel and heavymet castle, remove both sources.
10. Place each in their own smaller lead castle with 1 inch thick walls.
11. Tape castles closed.
12. Double bag the castles.
13. Place each castle in its own steel paint can. Figure 4.3 shows the castles in the paint cans.

Figure 4.3: Paint can containing lead castle for transport underground.

14. Place each can in its own shoulder bag.
15. Two people, each carrying one of the shoulder bags, carry the source to the lab.
16. Go into the carwash. The carwash is the room which sits on the boundary between the mine and the clean area where the SNO facility is located.
17. Remove the lids on the paint cans.

18. Open the outer bag, and pull it back so that the inner bag can be easily removed without touching the outer.
19. Leave the sources, continue through the change rooms following the normal SNO clean room procedures into the SNO lab.
20. Retrieve the source by reaching into the carwash and taking out the inner bag (containing the lead castle) without touching the outer bag.
21. Remove the inner bag, from the outside of the lead castle.
22. Bring the castle into the control room.
23. Steps 20 through 22 were done for each castle.
24. Bring a clean tray out from the deck clean room (DCR). The room at the centre of the SNO deck from which all sources are deployed is a class 500 clean room called the deck clean room.
25. Open each castle.
26. Place the sources (still contained in two air tight double bags) on the clean tray.
27. Bring the tray containing both sources into the DCR.

4.5 First Preparation Run

The first preparation run took place July 28, 2005 to August 3, 2005. It was done to make sure no materials were forgotten or overlooked during design and preparation.

It ensured that all the necessary materials were brought underground ahead of time. The procedures as discussed in Sections 4.2 to 4.4 were followed when dealing with the sample.

For this run, the sources were transported underground 5 days after activation. Later runs were transported 3 days after activation, and thus were 9 times more active. Consequently, we could use a smaller lead castle with half inch thick walls for transport. This run had two 1.25 ml samples activated for use at site. We had planned to have a third sample, but it did not get deployed in the reactor at RMC properly and thus was not exposed to any neutrons.

Before the source had left Queen's the strength was measured using a germanium detector and it was determined that the strength at the time of activation was 12.1 MBq.

The DCR must be cleaned before any source that will go into SNO can be brought in and exposed. The procedure to clean the DCR is:

1. Dust mop the DCR.
2. Wet mop the DCR floors.
3. Damp mop the DCR walls using ultra pure water.

In February 2003 a ^{222}Rn source was injected into the D_2O(12). Much of the injection apparatus developed for that calibration was reused for this experiment. The umbilical still had the teflon tube from this experiment in place. The umbilical is a tube that connects the source to equipment in the DCR so external equipment can drive the calibration sources. The equipment had to be inspected and tested, according to the following procedure:

1. Transport the radioactive brine as detailed in Section 4.4.
2. All present in the DCR must put on gloves.
3. Visually inspect the teflon tube that will be used to inject the sample into the D_2O, looking for kinks and other flaws.
4. Flow nitrogen gas, N_2, with a pressure of 5 PSI through the tubing for 5 minutes to take as much moisture as possible out of the tube.
5. Attach the injection device (see Section 3.5) to the tubing.
6. Blow N_2 through the injection system to check the connections for leaks.
7. Obtain 2.5 litres of degassed D_2O from the water group. It will be delivered in two 1 litre bottles and one 0.5 litre bottle. All bottles will be supplied and labelled by the water group.
8. Weigh all of the bottles. Record weights and the bottle names (as written on the bottle by the water group).
9. Pour the two 1 litre bottles into the 2.5 litre mixing vessel.
10. Weigh the empty bottles to determine the exact amount that was poured into the 2.5 litre vessel.

The remaining 0.5 l of D_2O is used to flush out the teflon tube. The SNO standard for cleaning pipes is to flush them with 3 times the volume or the pipe. To do this follow the procedure in Table 4.4:

1. Put on clean gloves.
2. Attach a tube to a peristaltic metering pump.
3. Place the other end of the tube into the 0.5 litre bottle containing the D_2O.
4. Attach a tube from the injection system to the pump.
5. Place a recovery bottle under the injection device to retrieve all the used D_2O.
6. Place the 0.5 litre bottle on the scale. Record the mass.
7. Fill the teflon tube. This should require 72.1 g of heavy water. This number was obtained by measuring how much D_2O left the bottle during the first prime of the tube. This was the only way to determine this because the tube was already in place and the length was unknown. The standard for cleaning tubes is SNO is 3 times the mass. This procedure exceeds that standard and calls for 5 times this mass. Calculate and record the mass for flushing.
8. Flush the tube with 5 times the amount of water in the teflon tube.

Table 4.4: Procedure to flush teflon tube.

Samples of ^{24}Na were then taken to be measured at Queen's and Guelph. To take the samples follow the procedure in Table 4.5:

- **Location:** DCR
- **Apparatus:**
  - 2.5 litre mixing vessel.
  - Hand drill.
  - 3 ultrasonically cleaned 30 ml bottles.
  - Peristaltic pump.
  - About one meter of teflon tubing that can be cut into lengths
  - 2 scales, one accurate to 0.1 g (4 kg max.), one accurate to 0.01 g.
- **Number of People:** Two.

1. Determine the approximate mass of the sample required.
2. Put on clean gloves.
3. Place the filled 2.5 litre vessel on the scale.
4. Person A holds the bag containing the source.
5. Person B uses a razor to slice the bag open.
6. Person B holds a clean tray below the bag containing the source.
7. Person A presses on the bag below the source and slides their fingers up to squeeze the source onto the tray.
8. Each person changes their gloves.
9. Person A unscrews the bottle of the ^{24}Na source.
10. Person B uses a 12 inch needle to remove the radioactive brine.
11. Person A opens any of the 4 valves on the 2.5 litre vessel.
12. Person B injects the brine through the valve.
13. Person A closes the valve.
14. Person A connects the hand drill to the mixing rod and stirs for two minutes.
15. Person B places the tube from the peristaltic pump, which brings liquid into the pump, through any one of the valves on the 2.5 litre vessel.
16. Person B puts an ultrasonically cleaned 30 ml bottle on the scale accurate to 0.01 g. Record its tare weight.
17. Person A places the tube from the peristaltic pump, which brings liquid out of the pump, into the 30 ml bottle.
18. Person A switches on the pump and fill the 30 ml bottle.
19. Person A turns off the pump
20. Person B removes the tube form the bottle and record the weight.
21. Person B labels the 30 ml bottle with the date, contents, tare weight and full weight.

22. If a second sample is required, determine the mass, and repeat steps 16 to 21.

Table 4.5: Procedure to obtain samples from diluted ^{24}Na brine

Bring one bottle brought back to Queen's to be counted using the germanium detector. The sample that is being shipped to Guelph must be handed over to the water group at this time. The legal requirements of handling the D_2O on the surface, limit the personnel who can handle the D_2O. The water group will send the other sample to Guelph University to be counted using their germanium detector, described in Section 3.6.3.

4.5.1 Results of First Preparation Run

This run allowed the injection device, mixing vessel, delrin can, and extra tubing to be transported to site and underground. Some of the issues that were revealed included the procedure did not include notification of the SNO site radiation officer, there was too much D_2O poured into the mixing vessel, so that the total mass exceeded the 4 kg maximum of the scale, the connections between the injection device and the teflon tube that was brought from Queen's did not work, and there was confusion between the calibration and water groups about obtaining and handling the D_2O.

These problems were easy to solve. The procedure to notify the radiation officer was put in place. The vessel would be filled on a 4 kg max. scale for future fillings. The proper connectors were obtained and put in place. The water group shift coordinator and shift supervisor should always be notified of the schedule so that they could prepare the D_2O for the experiment.

The delrin can was not deployed, so the detector response and strength determination could not be done using SNO. The sample that was brought back to Queen's was too weak for the germanium detector to get an accurate measure of strength. This lead to the conclusion to use the germanium detector underground, which was just commissioned.

It was then decided to make these modifications and to do another preparation run.

4.6 Second Preparation Run

The procedure followed for this preparation run was more extensive and included the changes due to issues with the first preparation run. This started on September 7, 2005, and lasted until September 13, 2005. Most of the supplies were already underground. The schedule was followed as detailed in Table 4.2. The activity was measured at Queen's to be 12.1 ± 1.5 MBq at the time of activation. The sample was packed in a one inch thick walled lead castle for transport underground. To calculate the activity of the ^{24}Na we used equation 4.1.

$$\frac{A_{^{24}Na}}{A_{^{60}Co}} = \frac{R_{^{24}Na}}{R_{^{60}Co}} \frac{E_{\gamma}(^{24}Na)}{E_{\gamma}(^{60}Co)} \tag{4.1}$$

where A is the activity, R is the rate, and $E_{\gamma}(^{60}\mathrm{Co})$ and $E_{\gamma}(^{24}\mathrm{Na})$ are the energies of the ^{60}Co and ^{24}Na lines measured. Here we have assumed that the efficiency, ϵ, goes as $\frac{1}{E_{\gamma}}$(15). The uncertainty in the rates comes from the limitation of the accuracy in determining the area of the peak, each was given a 5% error. The activity of the ^{60}Co source is said to be known to 5%, and the ratio of efficiency plus geometrical corrections due to the difference between the calibration source and the ^{24}Na source was given a 10% uncertainty. These were added in quadrature to give an 12% error on the measured ^{24}Na source strength.

The procedure followed for the second preparation run was:

- **Location:** DCR.

- **Apparatus:**

  - 2.5 litre mixing vessel.
  - N_2 gas.
  - hand drill.
  - 2 ultrasonically cleaned 30 ml bottles.
  - Ultrasonically cleaned delrin canister (inner and outer).
  - Peristaltic pump.
  - About one meter of teflon tubing that can be cut into lengths.
  - 2 scales, one accurate to 0.1 g (4 kg max.), one accurate to 0.01 g.
  - 12 inch needle.

- **Number of People:** Two.

1. Transport the radioactive brine as detailed in Section 4.4.
2. Go in the DCR.
3. Put on gloves.
4. To reduce exposure to the air underground, seal the 2.5 litre vessel.
5. Connect the N_2 flow, which also has a swagelok connector, to one of the valves on the 2.5 litre vessel.
6. Set the N_2 flow to 5 PSI of pressure, and turn it on.
7. Slowly open the valve allowing the gas into the 2.5 litre vessel.

8. Slowly open a second valve to allow the gas to flow through the vessel and exhaust into the DCR.
9. After one minute close the second valve.
10. Close the valve that has the gas connected and disconnect the gas, leaving the vessel under pressure.
11. Bring the vessel to the water group.
12. The water group connects a D_2O nozzle directly to the 2.5 litre vessel through one of the swagelok connectors.
13. Place the 2.5 litre vessel on a 4 kg maximum scale.
14. The water group opens the valve on the 2.5 litre vessel.
15. The water group opens the valve on their water system to start the flow of D_2O.
16. Monitor the weight of the vessel until it has a total mass of approximately 4 kg including the piping assembly.
17. The water group turns off the D_2O flow.
18. Close the valve on the 2.5 litre vessel.
19. Disconnect the hose through which the D_2O was injected.
20. Bring the vessel into the DCR.

21. Take a 30 ml sample in a polyethylene bottle and a 10 ml sample in the delrin can following the procedure in Table 4.5. The polyethylene sample should be labelled, and will be used for germanium counting at SNO. The delrin can will be deployed into SNO. It cannot be labelled, so be certain to record the weights into the electronic and paper log books for archival analysis.

22. Wipe the outside of the delrin can with UPW.

23. Measure the cloth with a beta-gamma counter to verify there was no spill. There should be no activity above background detected.

24. Put this can into the outer can delrin can to create a double seal.

Following the procedures in Section 8.8.11 of the calibration procedure manual, the delrin can was attached to the stem (Figure 4.4), the umbilical retrieval mechanism (URM) was mounted onto the glovebox, and the source was deployed into the heavy water. The URM is a removable chimney on the glovebox where sources are mounted on the pulley system, then placed on the glovebox to be deployed in the SNO detector. The glovebox is located at the top of SNO and is the access point to deploy sources into the D_2O.

The second sample was brought to the germanium detector underground to be measured. To prepare this sample, follow the procedure in Table 4.6:

Figure 4.4: The stem is a teflon rod on the end of a pulley system which allows calibration sources to be moved through two planes inside the D_2O.

1. Obtain an ultrasonically cleaned Marinelli beaker.
2. Obtain 1 litre of D_2O from the water group.
3. Put on clean gloves.
4. Weigh the full 1 litre bottle. Record this measurement.
5. Pour the sample from the 30 ml bottle into the Marinelli beaker.
6. Pour the pure D_2O into the Marinelli beaker stopping 3 cm from the top.
7. Snap on the lid to the beaker.
8. Weigh the empty 30 ml bottle, determine how much brine is in the beaker.
9. Weigh the 1 litre bottle to determine how much D_2O was put into the beaker.
10. Wrap the beaker in a bag and seal it.
11. The operators of the germanium detector will bring the full Marinelli beaker from the DCR to the germanium detectors and measure.

Table 4.6: Procedure to fill a Marinelli beaker

The source was counted, and the spectra recorded every 4 hours. The early spectra were used to measure the ^{24}Na activity, while the later counts, when the source had died away, were used to determine the background and to ensure that there were no long lived contaminants.

The delrin can then had to be removed from SNO after being in the detector overnight. Following the procedures in Section 8.8.12 in the calibration procedures manual. Once the source is out of the detector:

1. Remove delrin can from stem.
2. Dry the delrin can.
3. Weigh the delrin can. Record this value.
4. Open lid of outer delrin can.
5. Take out inner delrin can.
6. Weigh and record the mass of the inner delrin can.

Table 4.7: Procedure to handle delrin can once removed from SNO.

4.6.1 Results from Second Preparation Run

Day One

The 2.5 litre mixing vessel was filled by the water group to a mass of 3993.7 g including the hosing used to fill it. While the brine was injected using a syringe bubbles were noticed, meaning there were trace amounts of mine air being transferred as well.

Day Two

The preliminary results from the germanium detector underground for the diluted ^{24}Na sample only exhibited the expected lines, that is the two gamma peaks, their associated escape peaks, the sum peak, and a ^{40}K line. The spectrum is shown in Figure 4.5. The ^{24}Na gamma lines at 1368 and 2754 keV were seen. These are lines 2 and 5 in Figure 4.5. Both of the gamma-rays are emitted from the ^{24}Na decay simultaneously. If both are fully captured in the crystal one observes an energy which is equal to the sum of the two gamma rays. This is the sum peak, shown as line 7 in Figure 4.5.

Another possibility is that these gamma rays interact with the germanium via the pair production reaction and produce an electron and a positron. If one of these annihilates inside the crystal two 511 keV gamma-rays are produced. If one of these gamma-rays escape we lose this energy this creates the single escape peak. This is seen as line 5 in Figure 4.5). If both escape than we see the double escape peak ($2 \times$ 511 keV lower then expected, line 4 in Figure 4.5). If the pair production occurs in the shielding outside of the crystal, it is possible a positron comes into contact with an electron and annihilates releasing two gamma rays each with 511 keV of energy. If either of these gamma-rays come into the crystal we will see the 511 keV line, line 1 in Figure 4.5. A background which is virtually impossible to eliminate is ^{40}K, which is present in all rocks and is also seen in our spectrum as line 3.

The strength of the ^{24}Na was estimated using the 1368 keV line from the ^{24}Na measurement and obtaining the efficiency by interpolating between the 1115.5 keV

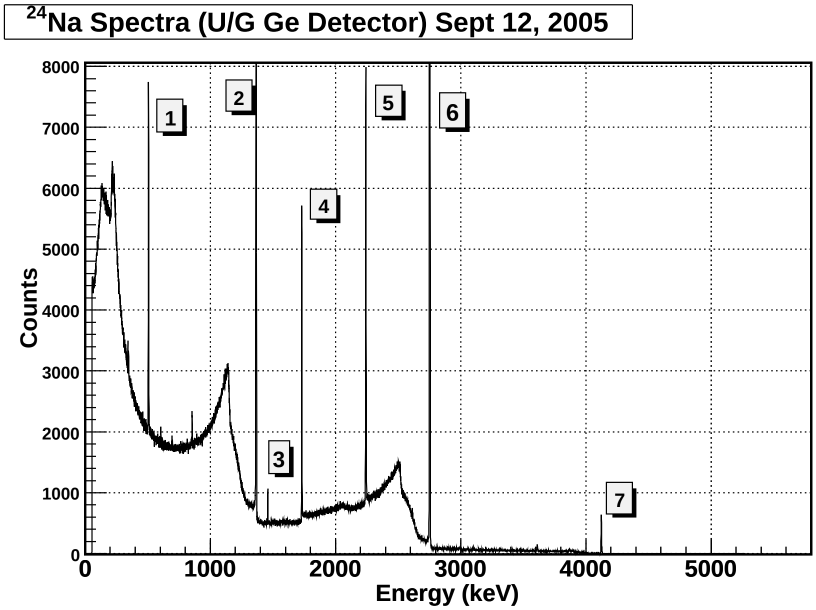

Figure 4.5: Underground Germanium Detector Results of ^{24}Na Sample from the Second Preparation Run. The labels are: 1. 511 keV annihilation 2. 1368 keV gamma ray 3. ^{40}K 4. Double escape 5. Single escape 6. 2754 keV gamma ray 7. Sum peak

^{65}Zn and the 1836.1 keV ^{88}Y lines of the calibration source measurement.

At the time of ^{24}Na measurement, the germanium detector was in its commissioning phase and thus no calibration had been done. The energy and efficiency calibration with a known radionuclide source was taken four days after the ^{24}Na sample. There were no geometric, or self absorption corrections made in this preliminary strength estimate.

There was a gain shift between the two measurements, thus the channel to energy calibration was different for each. The calibration done in Figure 4.5 uses the known energy of the ^{24}Na gamma peaks to make the channel to energy conversion. The calibration of the radionuclide source in Figure 4.6 uses the ^{65}Zn and the ^{88}Y lines to make the conversion. The other elements in the sample are mentioned in Section 3.6.2.

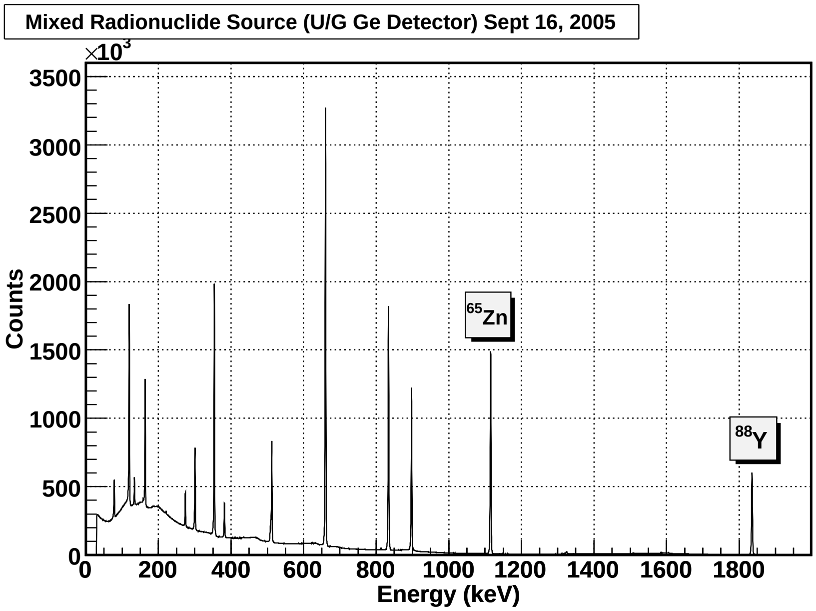

Figure 4.6: Underground germanium detector results of known radionuclide source.

Energy (keV)	Known Rate (γ/sec)	Counts	Livetime	Efficiency, ϵ
1115.5	4625	11922433	411634	0.006
1836.1	7976	5732327	411634	0.002

Table 4.8: Data to calculate efficiency of underground germanium detector.

Energy (keV)	Calculated Rate (γ/sec)	Counts	Livetime	Efficiency, ϵ
1368.6	386	587525	325286	0.005

Table 4.9: Calculated strength of ^{24}Na sample determined from the second preparation run

In Table 4.8 the efficiency, ϵ, was defined as $\epsilon = \frac{\frac{counts}{livetime}}{known\ rate}$. Then by using the two calculated efficiencies and linear interpolating between them we are able to determine the efficiency of the ^{24}Na 1368 keV line. The activity of ^{24}Na decay, $R_{^{24}Na}$, can then be determined using the information in Table 4.9, and $R_{^{24}Na} = \frac{\frac{counts}{livetime}}{\epsilon}$. The rate of the 30 ml sample of ^{24}Na was 386 ± 31 Bq. Here the error is due to the uncertainty in the calibration source strength of 3%(16) and geometrical and gain shift corrections. We expect to inject approximately 950 ml into the D_2O. This gives a correction factor of about 30, corresponding to an injected activity of 12 200 ± 1000 Bq. There was a strength of 12.5 ± 1.0 MBq 10 half lives earlier, at the time of activation. After this trial the detector was commissioned and ready for the next ^{24}Na measurement.

The Delrin can, which had been just removed from the D_2O, had the O-ring seals around the lids of the can verified to be secure. D_2O was observed to have made it into the screw holes but not past the O-ring seals behind them. We recorded the weights before and after deployment and there was no evidence of leakage. The difference in the weights is 0.04 ± 0.02 g heavier after deployment. This small amount is thought to be within threads of the screw holes or screws where we could not eliminate all traces of D_2O.

It was decided after the second preparation run to increase the activity at activation to 18 MBq. This would ensure enough statistics, and would not affect the schedule due to the short halflife of ^{24}Na.

4.7 The ^{24}Na Injection Experiment

The actual ^{24}Na injection experiment started September 28, 2005. The activation and handling was described in Sections 4.2 and 4.3. The source strength of the activated ^{24}Na was measured at Queen's to be 19.3 ± 2.3 MBq using the method as in section 4.6. The schedule that was followed is shown in Table 4.3.

The procedure to dilute the ^{24}Na and remove three samples is given in Table 4.10:

- **Location:** DCR.
- **Apparatus:**
    - 2.5 litre mixing vessel.
    - N_2 gas.
    - Hand drill.
    - 2 ultrasonically cleaned 30 ml bottles.
    - Ultrasonically cleaned delrin canister (inner and outer).
    - Peristaltic pump.
    - About one meter of teflon tubing that can be cut into lengths
    - 2 scales, one accurate to 0.1 g (4 kg max.), one accurate to 0.01 g.
    - 12 inch needle.
- **Number of People:** Three.

1. Bring ^{24}Na source to site and underground and into the DCR following the procedures in Section 4.4.
2. All three persons put on clean gloves.
3. Dust mop the DCR to prepare for the open source.
4. Damp mop the large drip tray.
5. Bring it to the table where the work will be done.
6. All people change gloves.
7. Bring the two scales, one 4 kg maximum accurate to 0.1 g, and one 2 kg maximum accurate to 0.01 g, to the table and place in large the drip tray.
8. Bring the two ultrasonically cleaned empty 30 ml bottles to the drip tray.
9. Set the peristaltic metering pump on the table.
10. Put the ultrasonically cleaned syringe in the large drip tray.
11. All people change gloves before touching source.
12. Person A holds the bag containing the source.
13. Person B uses a razor to slice the bag open.
14. Person B holds a clean tray below the bag containing the source.
15. Person A presses on the bag below the source and slides their fingers up to squeeze the source onto the tray.
16. All three people change their gloves.
17. Repeat steps 14 through 18 to remove the second air tight bag.
18. Repeat steps 14 through 19 for the second source.
19. Connect the N_2 flow, which also has a swagelok connector, to one of the valves on the 2.5 litre vessel.

20. Set the N_2 flow to 5 PSI of pressure, and turn it on.
21. Slowly open the valve allowing the gas into the 2.5 litre vessel.
22. Slowly open a second valve to allow the gas to flow through the vessel and exhaust into the DCR.
23. After one minute close the second valve.
24. Close the valve that has the gas connected and disconnect the gas, leaving the vessel under pressure.
25. Bring the vessel to the water group.
26. The water group connects a D_2O nozzle directly to the 2.5 litre vessel through one of the swagelok connectors.
27. Place the 2.5 litre vessel on a 4 kg maximum scale.
28. Record this tare weight.
29. The water group then opens the valve on the 2.5 litre vessel.
30. The water group turns on the valve to start the flow of D_2O.
31. Monitor the weight of the vessel until it has a total mass of just under 4kg including the piping assembly.
32. Record this weight.
33. The water group turns off the D_2O flow.
34. Close the valve on the 2.5 litre vessel.
35. Disconnect the hose the D_2O was injected through.
36. Bring the vessel into the DCR.
37. Place the 2.5 l vessel on the scale in the large drip tray. (Note that in previous attempts the full weight was measured with both the scale in the DCR, and the scale the water group used while filling. These weights were different, as shown in Tables 4.11 and 4.12. The values obtained with the scale in the DCR are the only ones used in all further analysis.
38. All people in the DCR change their gloves.

39. Bring the small tray containing the brine to the large drip tray.
40. Connect the N_2 flow hose to the mixing vessel.
41. Turn on the flow to 5 PSI.
42. Person C opens valve allowing the N_2 into the 2.5 litre vessel.
43. Person C then opens a second valve slightly to allow the gas to flow through.
44. Person A opens the first bottle containing the sample.
45. Person B uses the syringe to draw up the sample.
46. Person C then opens a third valve.
47. Person B puts the needle into the water.
48. Person B injects the source into the mixing vessel.
49. The needle is removed, and the valve the needle was through is closed.
50. Steps 45 through 50 are repeated for the second sample.
51. All present change their gloves.
52. Person A closes all valves on the mixing vessel.
53. Person B connects a drill to the mixing rod, and mixes for two minutes.
54. Disconnect drill.
55. Allow N_2 to flow through the 2.5 l vessel as in steps 43 and 44.
56. Connect the outgoing side of the pump to a 1 meter teflon tube.
57. Connect a teflon tube to the incoming side of the pump and slide it through one of the valves until it reaches the bottom of the mixing vessel.
58. Fill two ultrasonically cleaned 30 ml bottles using the procedure in Table 4.5, steps 12 to 19.
59. Weigh the delrin can, all parts included.

60. Weigh the inner can.

61. Fill the delrin can using the procedure in Table 4.5, except fill it with 10 g of the brine, and it cannot be labelled. Record these weights in the logbooks.

62. Give the water group a 1 litre stainless steel thermos to fill with pure D_2O. This is to allow them time to prepare, and the stainless steel will not allow ^{222}Rn to diffuse into the water.

Table 4.10: Procedure for diluting ^{24}Na brine and removing three samples.

Tare	2473.6 g
Full	3991.3 g
Time	0615 h
Port	D-065H

Table 4.11: Water group measurements of the 2.5 l vessel before and after filling. The uncertainty on the mass is ± 0.1 g, and ± 1 minute on the time.

Tare	2284.2 g
Weight of Tube	192.8 g
Full (With Filling Tube)	3993.7 g
Full (Without Filling Tube)	3800.9 g
Full (With Brine, Without Filling Tube)	3804.5 g
After 3 Samples Removed	3723.0 g
After priming teflon tube	3645.0 g
After ECA runs (2 hours later)	3646.7 g
After ECA with N_2 tube and injection hose attached	3692.4 g
After Injection (Nothing attached)	2678.0 g

Table 4.12: Measurement made in DCR. The amount injected into SNO's active volume is 968.7 ± 0.1g. This obtained from the After ECA run and the After Injection values. These are the values to be used for analysis. The measurement was made on a scale accurate to 0.1 g, the error is ± 0.1 g. The ECA is an electronics calibration that was done just before the injection.

4.7.1 Measurements Taken during ^{24}Na Run

Tables 4.11 through 4.15 show the measurements taken during the dilution phase in the 2.5 litre vessel and the amount of diluted brine removed to be used as samples to measure the source strength.

Table 4.12 also shows the before and after weights that are used to calculate the amount of brine injected. The critical values here are the before measurement (After ECA run) and the after measurement (After Injection).

Tare	29.07 g
Full	39.43 g
Filling Time	33 sec
Sample Mass	10.36 g

Table 4.13: Measurements taken of the 10 ml delrin can. The measurement was made on a scale accurate to 0.01 g. The error is ± 0.01 g. This represents 1.039% of total injected volume.

Tare	11.11 g
Full	41.73 g
Filling Time	1m38s
Sample Mass	30.62 g

Table 4.14: Amount sent to the underground Ge detector. The measurement was made on a scale accurate to 0.01 g. The error is ± 0.01 g. This is 3.160% of total injected volume.

Tare	11.18 g
Full	41.62 g
Filling Time	1m37s
Sample Mass	30.44 g

Table 4.15: Amount sent to the Guelph Ge detector. The measurement was made on a scale accurate to 0.01 g. The error is ± 0.01 g. This is 3.142% of total injected volume.

4.7.2 Californium and Contained Central Runs

On Friday September 30, 2005 one of the standard ^{252}Cf neutron point sources was placed in the center of the active volume. It was left there to collect data for 3 hours 38 minutes. We know this source strength very well, as 16.55 ± 0.08 neutrons/second on June 12, 2001.

On Monday, October 3, 2005 the ^{24}Na in the delrin can was lowered into the center of the active volume and left to count for 19 hours 40 minutes. When it was removed, it was reweighed as in Section 4.6.1. The sample weighed 78.56 ± 0.01 g before it was deployed and weighed 78.60 ± 0.01 g after. We attribute this difference to D_2O caught in the seams that we could not dry. This sample represents 1.069% of the total injected sample. The SNO detector measures neutrons that are captured in either the heavy water or the NCDs. Since the source geometry for the two runs was very similar, it is possible to compare the neutron capture rates as measured by SNO.

4.7.3 ^{24}Na Open Source Injection into the D_2O

On Tuesday, October 4, 2005 the ^{24}Na brine was injected in the D_2O of the SNO detector. The procedure to do this is in Table 4.16:

1. Obtain the full 1 litre stainless steel thermos from the water group.
2. Connect the teflon tube from the injection system to the out going side of the peristaltic pump.
3. Attach a teflon tube to the incoming side of the pump.
4. Put the tube from the incoming side of the pump into the thermos.
5. Place a recovery jar under the injection device.
6. Flush the injection system with 5 times its volume.
7. Take tube out of thermos.
8. Press tube to N_2 hose.
9. Blow the tube dry using N_2 gas.
10. Close and remove the recovery jar.
11. Put the 2.5 litre vessel on the 4 kg maximum scale.
12. Record the weight of the vessel.
13. Connect the N_2 hose to the 2.5 litre vessel.
14. Record the weight.
15. Open the valve to allow N_2 in.
16. Open a second valve slightly to allow the gas to flow through.
17. Open a third valve.
18. Place the teflon tube on the incoming side of the pump into the third valve.
19. Record the vessels weight.
20. Place a recovery bottle at the end of the injection system.
21. Prime the injection system with brine.
22. Record the vessels weight.
23. Mount the URM on the glove box.

24. Move the injection device to the desired position. The positions are listed in Table 4.17.
25. Subtract the desired amount to inject from the reading on the scale. This gives the target mass.
26. Turn on the pump.
27. Turn off the pump when the target mass is reached.
28. Record this new mass of the mixing vessel.
29. Step 24 to 28 were repeated until the injection plan was complete.
30. Move injection device out of D_2O.

Table 4.16: Procedure to inject ^{24}Na brine into the D_2O.

Z-Position (cm)	Target Factor (g)	Injected Weight (g)	Time
-550	210	214.7	$\sim$ 16m
-500	210	214.6	16m25
-450	210	214.5	16m29
-400	26	26.4	2m01
-350	26	26.4	1m59
-300	26	27.4	2m04
-250	26	27.2	2m03
-200	26	25.9	2m00
-100	26	26.8	1m59
0	26	27.0	1m57
50	26	27.4	1m57
100	26	27.3	1m57
150	26	27.4	1m56
200	26	28.5	1m58
250	26	25.9	1m40

Table 4.17: The ^{24}Na brine injection locations and deposited amounts.

To verify the amount of brine injected, we had planned on using the time of the pumping as well as the weight change on the scale. For this to work the pump must move the brine at a constant rate. Unfortunately, the times could not be used to verify the amounts injected due to inconsistent pumping rate. The times were recorded during priming and in the preparation runs, but discarded when the rate seemed to vary. For example, if we look at the ratio of time to mass we see that at point -500 cm the ratio is 0.0765, at -200 cm it is 0.0772, and at 250 cm it is 0.0645. The variation is about 15% where the uncertainty in the mass, ±0.1 g is only about 0.5% for the smallest mass (where the effect would be largest).

The target factor is the mass of brine we wanted in each location. The weights in Table 4.17 do not add up to the total injected mass of 968.7 g, as measured by comparing the weight before and after the injection. This is due to how these measurements were made. These were recorded as the manipulator was moving from point to point. The tube was still inserted into the 2.5 litre vessel and the tube rested on the table, so slight shifting could cause small variations in the weight measurement. The best values are the before and after measurements with no attachments to the vessel, as obtained from Table 4.12.

Chapter 5. RISK OF CONTAMINATION

Whenever any material comes into contact with the D_2O in the active volume of SNO there is a risk of adding a contaminant. This would cause another complication in determining the neutrino flux signal. As a precaution all materials are ultrasonically cleaned and tested for radioactivity. When dealing with an open source such as the ^{24}Na brine, there was an added concern.

The pure D_2O samples that were taken for the first and second preparation run were measured with a germanium detector at Queen's looking for any unexpected radioactivity that may have been produced by neutron activation in the RMC SLOWPOKE-2 reactor. While checking for these contaminants ^{222}Rn was observed. We were surprised to see this in our sample but had to treat this as a potential source of background. ^{222}Rn can dissolve into our sample and thus be injected into SNO during our experiment.

As we investigated further we found that none of the activity was unexplained, and there was no excess ^{222}Rn in the sample. However, after this was observed, we had to treat this carefully. The steps taken that lead to the belief of ^{222}Rn and the verification that it was not present are outlined below.

5.1 Early Concerns

On July 28, 2005, the first sample came back to Queen's from RMC. This sample contained two types of vials. One with the activated brine which was used for the first preparation run, the second was a pure D_2O sample. This D_2O sample was measured with a germanium counter at Queen's. At this time we relied on the *Canberra Genie 2000* analysis program which came with the germanium detector. This program chose a region around the peaks, and calculated its area. A background run was taken, in which the sample was removed from the detector. It was analyzed in the same way.

This analysis concluded there were lines from radon (^{222}Rn) decay. The strength of the line indicated that if injected, this would add 1 Bq/ml of activity. ^{222}Rn has a much longer halflife (3.82 days) than ^{24}Na (14.96 hours). This would cause significant problems from a long lived background as well as confuse the measurement for the NCD neutron efficiency. An even worse outcome would be if this ^{222}Rn was being sustained by radium (^{226}Ra). This has a halflife of 1600 years. The full decay chain can be seen in Figure 5.1.

This result seemed high so the data was reanalyzed. This time the peaks were located by eye, searching subjectively through the spectrum. The background spectrum has all of the lines identified and labelled in Figure 5.2. To compare this to the D_2O sample's spectrum the D_2O sample had to be scaled to the same livetime. The first step in the analysis was to subtract the background sample from the data sample, this was done using equation 5.1.

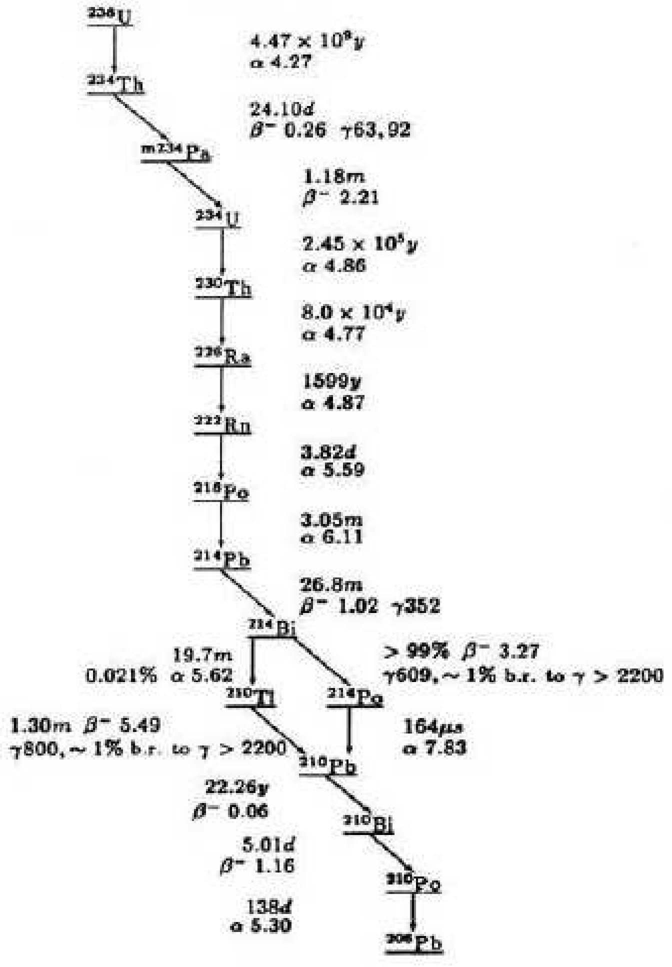

Figure 5.1: ^{238}U decay chain showing how the addition of radium can lead to significant background problems if added with the ^{24}Na.
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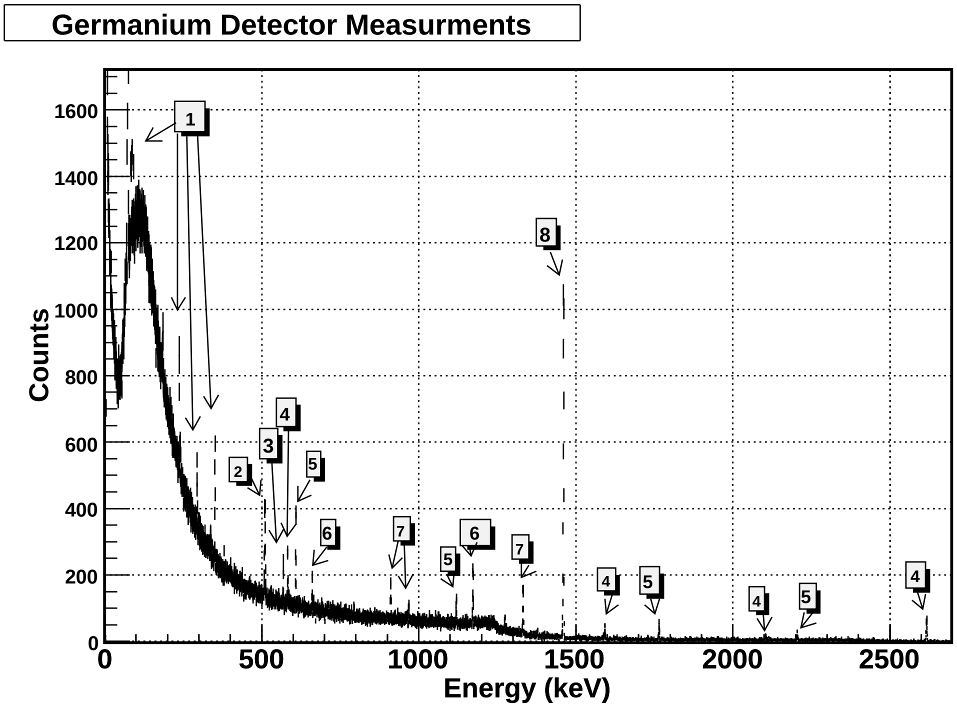


Figure 5.2: Background spectrum taken with the Queen's germanium detector. The labels for the peaks are:
1. ^{214}Pb 2. 511 keV $e^{+}e^{-}$ annihilation 3. ^{207}Bi 4. ^{208}Tl 5. ^{214}Bi 6. ^{137}Cs 7. ^{228}Ac 8. ^{40}K.

$$d_{i,new} = \frac{b_l}{d_l} d_{i,old} \tag{5.1}$$

where b_l is the background livetime, d_l is the data runtime, $d_{i,old}$ is the number of counts in bin i in the data spectrum before correction, and $d_{i,new}$ is the number of counts in bin i after the livetime has been scale to that of the background spectrum.

In Figure 5.3 we plot the livetime corrected background and data together. When looking at Figure 5.3 we see no lines in the D_2O that are inconsistent with the background spectrum. If we subtract the two plots in Figure 5.3, we get the plot shown in Figure 5.4. The germanium detector has a very narrow energy resolution and there were very small gain shifts between the measurements. This off set may be only of a channel or two, but when the difference is examined we see that some of the peaks are visible in the positive region and negative region. These peaks were found not to be statistically different in activity.

It was noticed that no two background measurements produced the exact spectrum, this led us to believe that the background contaminants changed over time, which made it impossible to rule out a low activity contaminant. This motivated the choice to use the germanium detector underground which was nearly background free.

5.2 Background Measurements with the Guelph University Germanium Detector

A sample was sent to Guelph to be analyzed after the second preparation run as discussed in Section 4.6. The results and analysis of the Guelph group are presented

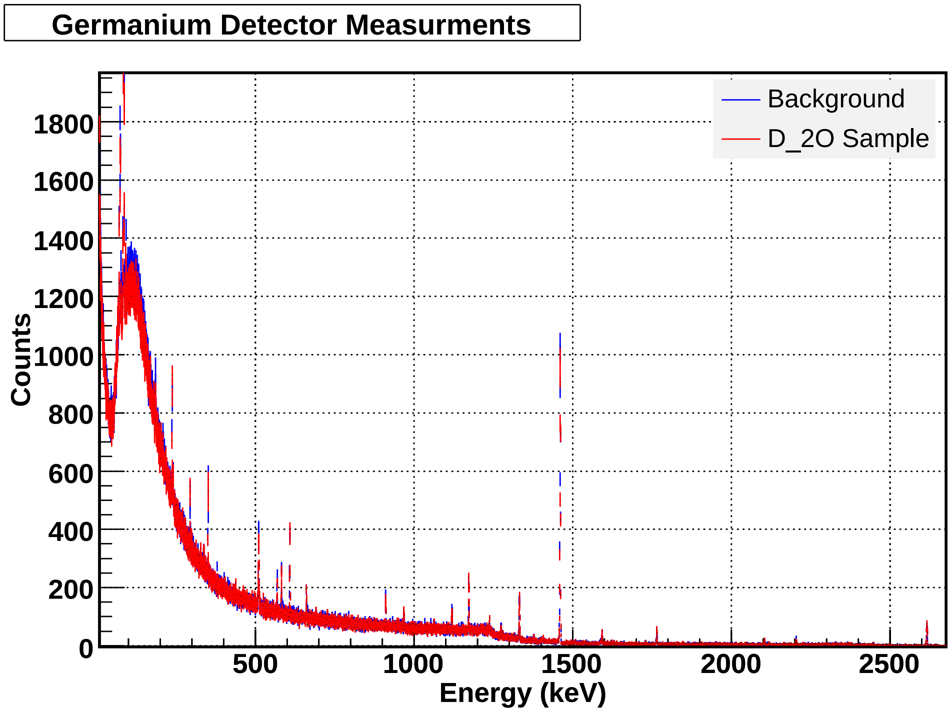


Figure 5.3: The background sample was measured at Queen's on August 2, 2005. The D_2O sample was measured on August 4, 2005. The livetime for the background was 91726 seconds, and 102214 for the D_2O sample. The scaling factor for the data was 0.89739.

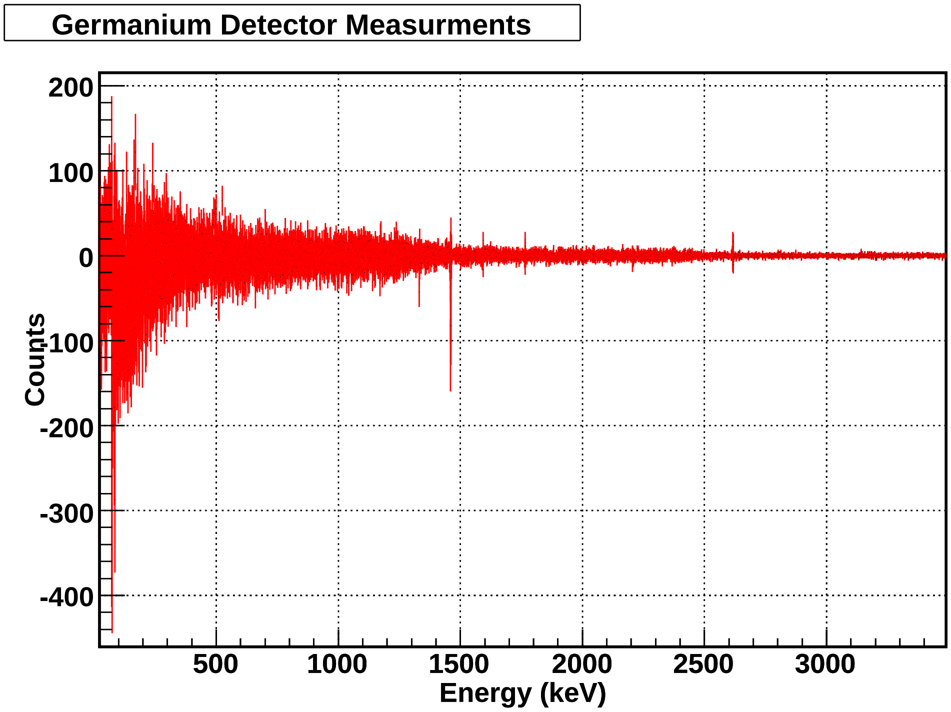


Figure 5.4: This is the difference between the two plots shown in Figure 5.3

here. The sample was counted in intervals of 15 hours. The results are given in tables 5.1 and 5.2. These show the net counts in the region of interest at the full energy peaks corresponding to 1.369 MeV and 2.754 MeV. The net counts are those above a linear background. The background was interpolated between the number of counts in the lower limit and the upper limit. A 2σ percentage error is also reported as a measure of error due to counting statistics.

The statistical error is given by $\sqrt{n}$, where n is the number of gross counts in the range of interest. This value represents a 1 σ uncertainty. To calculate a 2 σ statistical percentage error:

$$2\sigma\ \% = \frac{2\sqrt{n}}{n}$$

The counts in table 5.2 result from detector backgrounds such as cosmic rays, the activity within the shielding and any activity in the ^{24}Na sample. At the point this data was obtained the ^{24}Na had decayed by 28 half lives. The average counting rate in the 1.369 MeV region is found to be 127 counts per 15 hours, the 2.754 MeV region has 58 counts per 15 hours. This is the same rate as the system background with no sample in place.

The Guelph germanium detector observed no traces of activity other than ^{24}Na with an energy greater then 1 MeV. This combined with the underground germanium detector results gave us full confidence that our ^{24}Na was free of ^{222}Rn.

Time (Seconds)	Net Counts, 1.369 MeV Region	2σ %	Net Counts, 2.721 MeV Region	2σ %
53992	21777	1.57	11654	2.13
53989	10890	1.29	5982	1.72
53974	5356	1.20	3106	1.58
53979	2704	1.16	1470	1.53
53958	1251	1.15	689	1.51
53931	658	1.14	354	1.51
107933	446	1.14	271	1.51
53981	85	1.14	87	1.50
53981	41	1.15	45	1.51
53982	51	1.15	-35	1.51
53966	85	1.15	39	1.51
53981	9	1.15	-4	1.51
53981	29	1.15	4	1.52
53896	-11	1.15	7	1.52
53981	14	1.16	42	1.52
53982	69	1.16	-21	1.52
54041	9	1.16	-10	1.52
54041	27	1.16	-20	1.53
53921	7	1.16	77	1.53
53981	-21	1.16	-136	1.55
111561	-130	1.18	-86	1.56

Table 5.1: Net counts above linear background between counts in the lower and upper limit channels in each counting interval, with a 2 sigma percentage counting error.

Time (Seconds)	Net Counts in 1.369 MeV Region	Net Counts in 2.721 MeV Region
7142	17	5
54050	136	58
53952	131	60
53981	115	60
53981	126	61
46805	108	44

Table 5.2: Remainder of counting after last set ended in power failure. Cumulative Net counts above linear background between counts in the lower and upper limit channels in each counting interval.

5.3 Results from the Underground Germanium Detector

When the second preparation run took place, a sample of the ^{24}Na brine was measured in the germanium detector underground, as discussed in Section 4.6.1. This sample was left in the Marinelli beaker, in a storage closet underground. This sample contained approximately 40 ml of the diluted brine and 1 l of D_2O. The seal on the beaker was a top that was pushed on. Before the ^{24}Na injection experiment described in Section 4.7.3, this sample was remeasured to look for any long lived activity, in particular evidence of radium supported ^{222}Rn daughters.

The results (Figure 5.5) using the net counts for ^{214}Pb and the gross counts for ^{214}Bi, showed that there were 0.1 decays/second of activity, which is about 9000 decays/day of ^{214}Bi. Scaling this up to the amount of brine in the 2.5 l vessel, about a factor of 50, we have 450,000 decays/day. The SNO limits for ^{214}Bi is 32,000 decays/day, this at first seemed like an order of magnitude too much ^{214}Bi. However, it was also unphysical, there is no reason to believe that the processing of the brine should significantly enhance the radon levels. We came up with the hypothesis that a small amount of mine air (100 Bq/m^3) was trapped in the bag that contained the Marinelli beaker, and that some air was also trapped at the top of the beaker. The sample was recounted without the bag. There was also a search for a ^{226}Ra line at an energy of 186 keV which could not be seen.

After ^{222}Rn daughters (^{214}Pb and ^{214}Bi) were seen in the underground germanium detector, the calculation was made, that if 900 ml of mine air was trapped in the beaker and the surrounding bag (in place to ensure that there was no leakage of the activity out of the beaker and onto the crystal) and the D_2O was at equilibrium with the air, meaning that the water has an activity of 34% of the air, there would be a total ^{214}Bi activity of 2000 D_2O + 2500 Air = 4500 ± 500 decays/day. We could not remove the air from the Marinelli beaker, so we had to use this calculation to know how much ^{222}Rn would be in the sample just from the exposure to air. The sample that was to be injected into SNO did not have this concern because the mixing chamber was sealed with a nitrogen cover gas, thus no exposure to mine air.

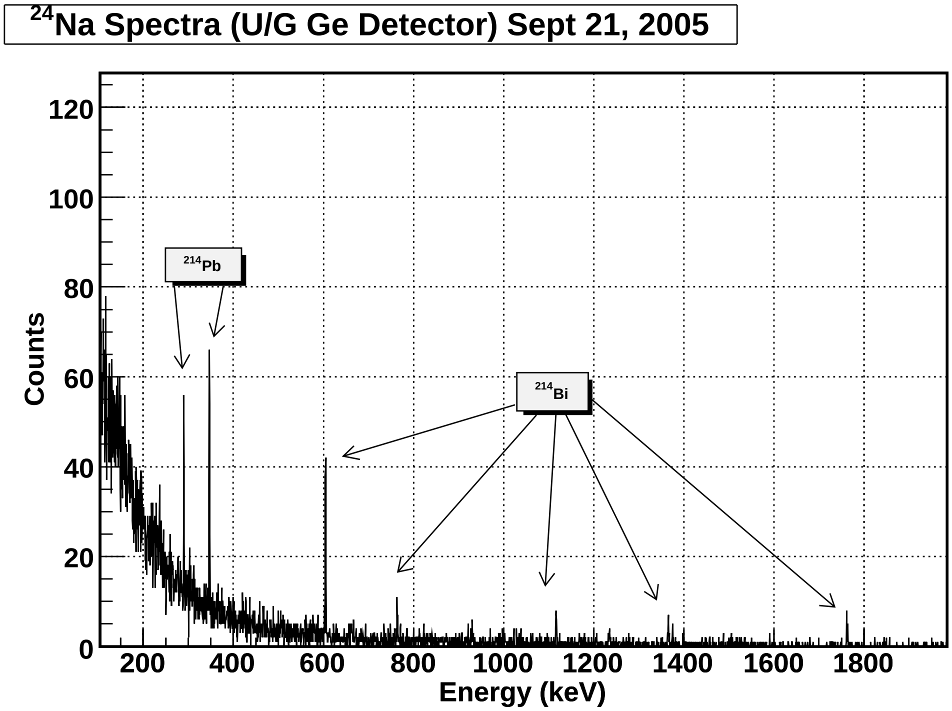


Figure 5.5: The sample was measured on September 21, 2005. This was 9 days (∼ 15 halflives) after it was taken from the 2.5 l vessel during the second preparation run.

The sample was placed in the detector the day before the ^{24}Na injection was to take place and the results were reexamined the morning of the injection. The results were consistent with the 4500 ± 500 decays/day as predicted, so we continued with the ^{24}Na injection.

Chapter 6. ANALYSIS

6.1 D_2O Mixing Results

6.1.1 Water Circulation During Mixing

The ^{24}Na was injected into the active volume on Tuesday, October 4^{th}, 2005. Initially much of the radioactive brine sank to the bottom of the AV. In order to use the calibration as a uniformly mixed source, it is necessary to measure the spatial uniformity. When the ^{24}Na decays it emits Cerenkov light, which is detected by the PMT array. This light was used to monitor the distribution of events. By looking at the timing of the photons from the event we are able to reconstruct the x,y,z position of the ^{24}Na activity.

The NHIT of an event is defined as the number of PMTs that observe light from the event within a 400 ns time window. A high NHIT means that the event had more energy. The analysis chain used an NHIT threshold of 20, which means that the lowest energy events were not included in the analysis. However, there were enough ^{24}Na events above this threshold that we were able to obtain statistically significant results on the ^{24}Na distribution.

Figure 6.1 shows the distributions of events in the detector, plotted as a function of vertical position z and cylindrical radius, $\rho = \sqrt{x^2 + y^2}$. The plots clearly show the initial distribution concentrated along the z-axis and largest at the bottom. They also show that the source seems to become more uniform in the horizontal components more quickly than in the vertical components. However, this plot has bins that have unequal volume, so one cannot directly compare the values in the different bins to see whether or not the sodium is mixed.

Figure 6.2 shows the distributions of events in the detector, plotted as a function of horizontal position x and vertical position z. These plots are more useful because they show the event rate in equal volume cubes, with a 50 cm slice taken along $y = 0$. Most of the activity is initially at the bottom of the spherical detector. The activity moves from the bottom, around the outside, and eventually into the middle.

Figure 6.3 shows the distributions of events in the detector, plotted as a function of horizontal positions x and y. These plots are also divided up into equal volume cubes, with a 50 cm slice taken along $z = 0$. Most of the activity is initially inside a cylindrical radius of 200 cm. This was expected because the activity initially gathered at the bottom of the AV. It was mixed from there and can be seen to swirl around the sides, and slowly into the middle.

To get an overall picture of the state of the radioactivity mixing, the active volume was divided into cubes of the size 1 m^3. When the radioactivity is uniformly distributed each cube should have the same number of events in a time period, varying only by statistical fluctuation. A Gaussian, as shown in equation 6.1, was used to fit to the distribution.

$$P(x) = Ae^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{6.1}$$

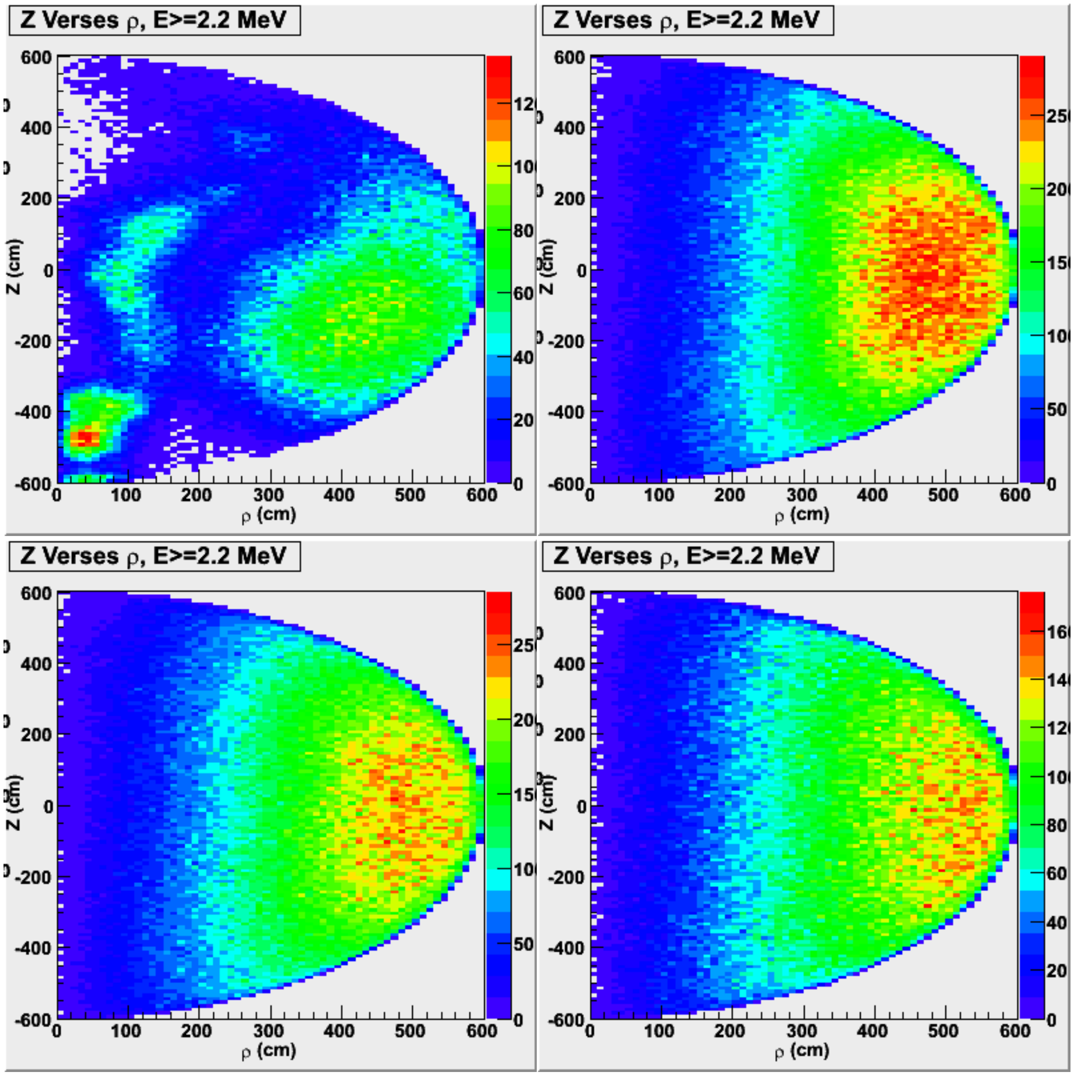


Figure 6.1: Location of radioactivity inside a radius of 600 cm, as a function of Z and ρ. The panels correspond to different times (in hours), starting in the top left to bottom right; $0 < t < 0.25$, $14.25 < t < 15.5$, $27.75 < t < 28.5$, $57 < t < 57.75$. The colour indicates the activity in the bin (counts/time)

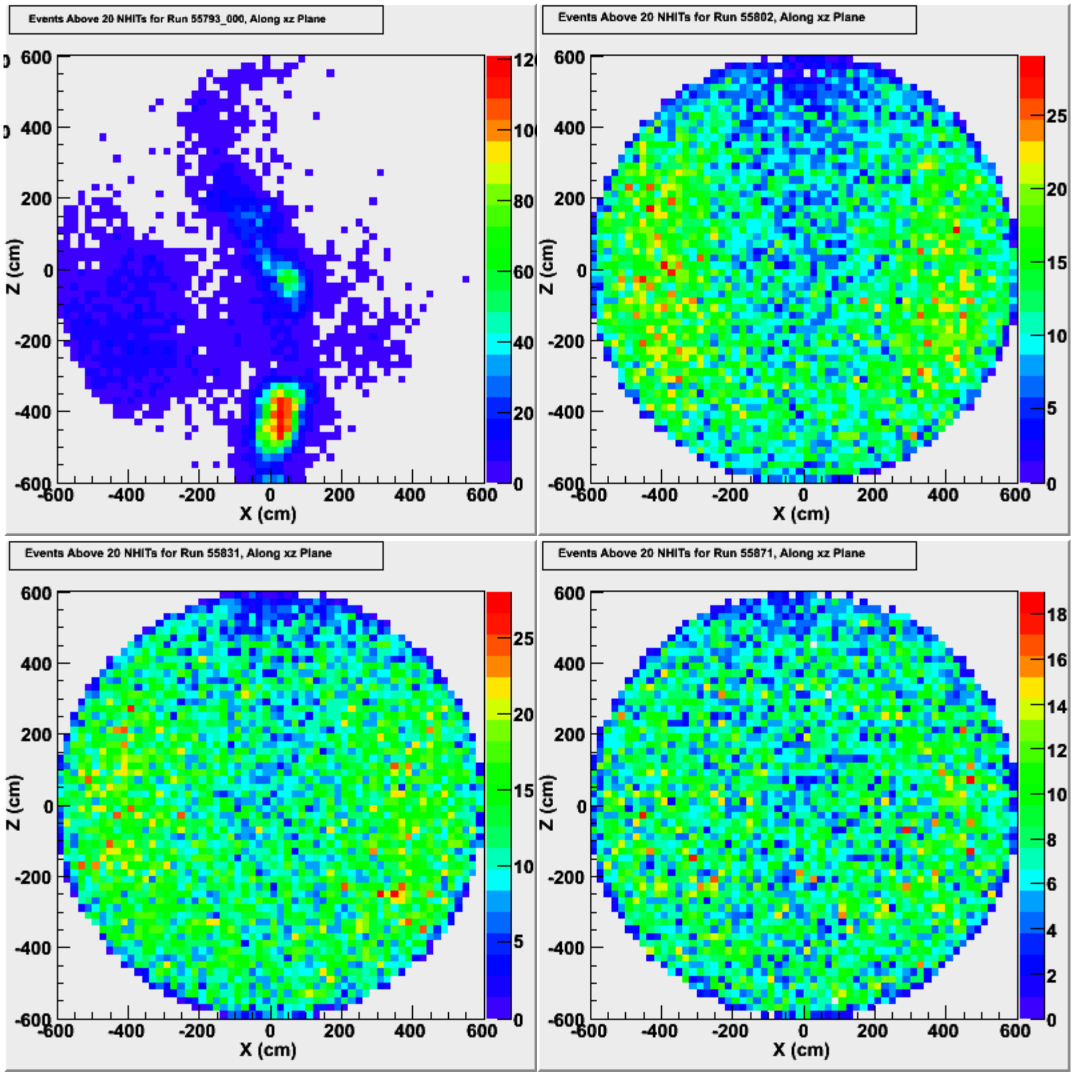


Figure 6.2: Location of radioactivity inside a radius of 600 cm, as a function of X and Z, in a slice along y=0. The panels correspond to different times (in hours), starting in the top left to bottom right; $0 < t < 0.25$, $14.25 < t < 15.5$, $27.75 < t < 28.5$, $57 < t < 57.75$. The colour indicates the activity in the bin (counts/time)

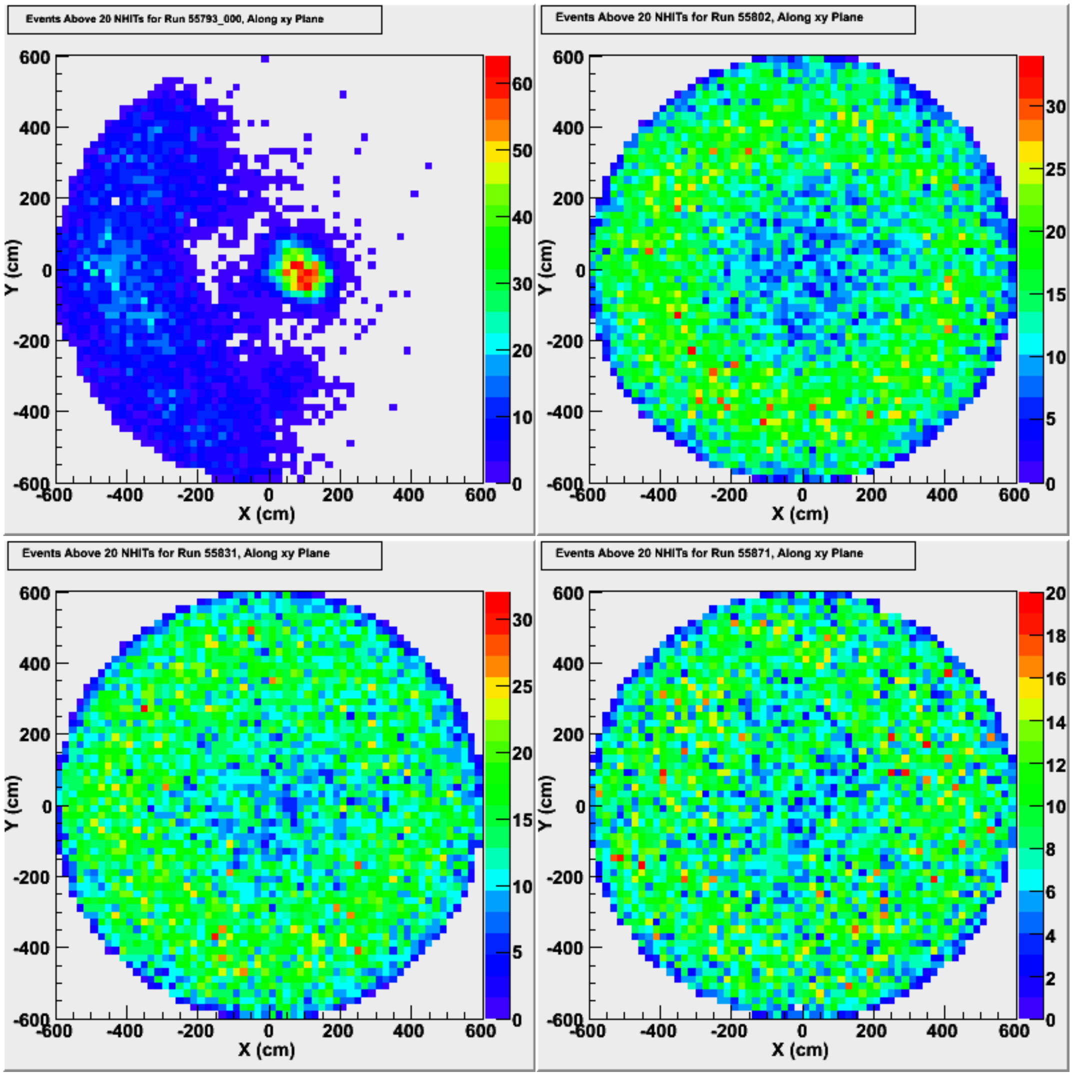


Figure 6.3: Location of radioactivity inside a radius of 600 cm, as a function of X and Y, in slice along z=0. The panels correspond to different times (in hours), starting in the top left to bottom right; $0 < t < 0.25$, $14.25 < t < 15.5$, $27.75 < t < 28.5$, $57 < t < 57.75$. The colour indicates the activity in the bin (counts/time)

The mean (or centroid) is represented by μ, the standard deviation by σ, and A is the amplitude. The standard deviation should be $\sqrt{\mu}$ if the rate is determined by the event fluctuation in decay of independent events. If it is wider than this, then some cubes have too much activity, while others still have too little. The progression of this distribution is shown in Figure 6.4.

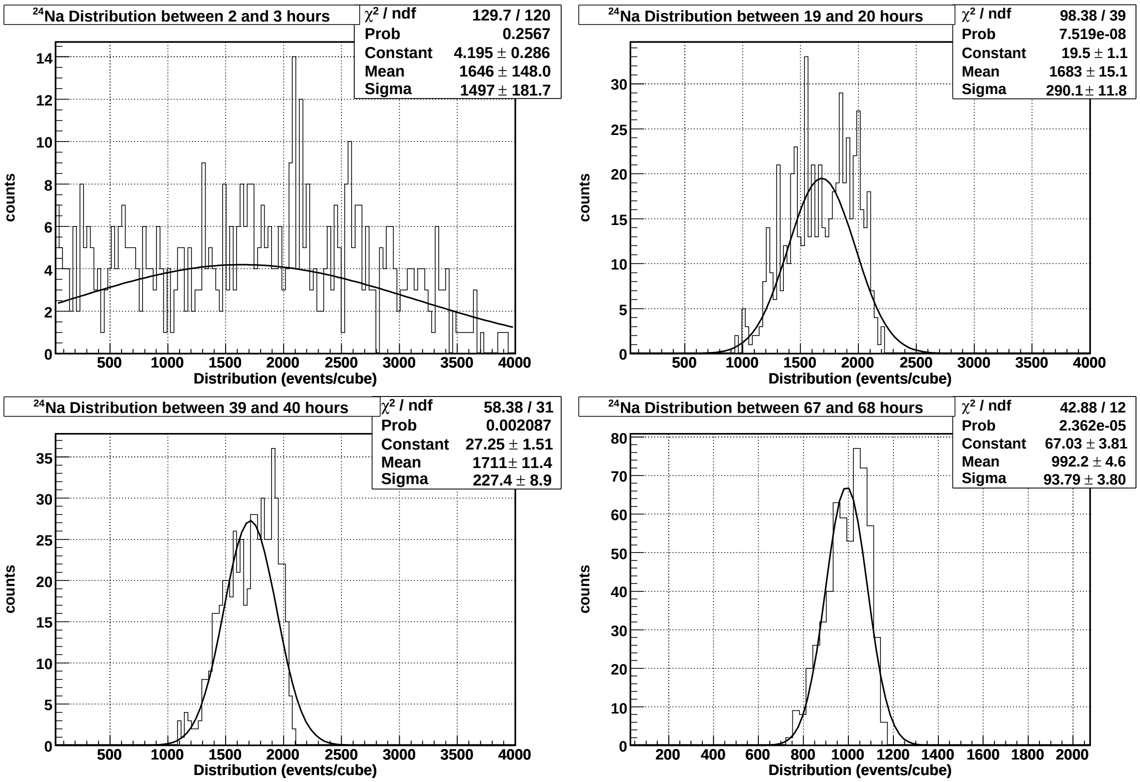


Figure 6.4: Progression of Radioactivity Distribution in the AV.

To determine how uniformly mixed the activity was the variable σ_{mix} was defined:

$$\sigma_{mix} = \sqrt{\frac{\sigma^2 - \mu}{\mu}} \tag{6.2}$$

where σ and μ are taken from equation 6.1. The progression of the distribution over the mixing period can be seen in Figure 6.5.

Events from the activity only occurred inside of the 600 cm radius. Thus, if a

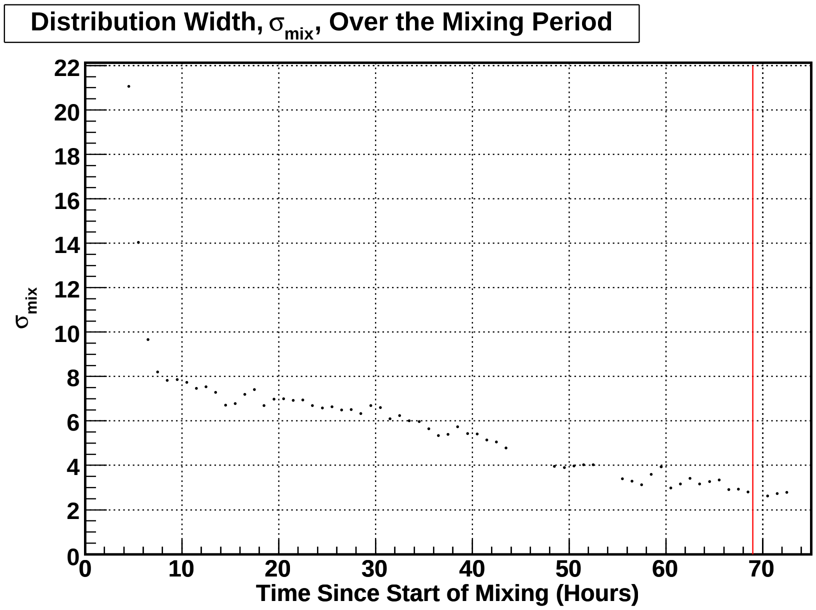


Figure 6.5: Mixing status of the activity over the entire mixing period. The red line indicates the end of mixing, the points to the right sample the distribution during the data taking period.

portion of a cube was outside then the cube would not be able to contain as many events as a fully contained cube. The elimination of these cubes was necessary so that we could determine when the radioactivity was evenly dispersed. If any part of the cube touched or was outside of a 600 cm radius it was removed from the analysis. 552 cubes remained after this cut.

6.1.2 Evidence of Uniformly Distributed Activity

At 12:00 on Friday, October 7, 2005, corresponding to 68 hours in Figure 6.5, σ_{mix} was no longer dropping. It is at this point we defined the activity as mixed. At this state we find $\sigma_{mix} = 2.8$. This is near what we would expect, as seen in a Monte Carlo calculation of a uniform distribution (Figure 6.6), σ_{mix} should be 2.6.

It was seen in the ^{222}Rn spike that PMT to PMT variation would not allow the

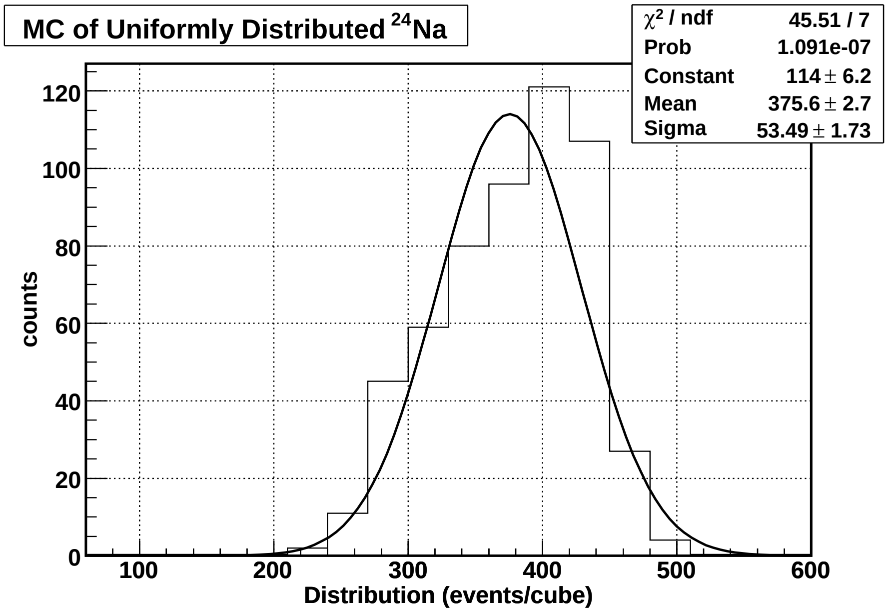


Figure 6.6: Monte Carlo example of uniformly distributed ^{24}Na. The histogram represents data, and the smooth curve is a Gaussian fit to the data.

volume to appear ideally mixed(12). Our experiment had additional complications because the NCDs will 'shadow' light. This affects the events that occur closer to the center more than those near the AV, since the light from events at the center must pass more NCDs to get to the PMTs. This creates the illusion that there is less activity in the center.

To further examine the distribution of the activity, we plot the x co-ordinate of each of the 552 cubes against the activity in that cube. In Figure 6.7, we expect a flat distribution along the x co-ordinate. What we have is a deficit of about 12% in the activity in the centre of the D_2O. This is evidence for shadowing by the NCDs.

This plot is also made for the distribution along the y-direction, Figure 6.8. The lower activity levels are present in the centre for the Y-direction as well. The x and y directions are expected to be the same because SNO is symmetric along these axis.

When looking at the cylindrical radius, ρ, we see the same effect as in the x and y directions. This is shown in Figure 6.9. This effect is expected since $\rho = \sqrt{x^2 + y^2}$. Like in the x-direction, this effect is due to NCDs shadowing the PMT array.

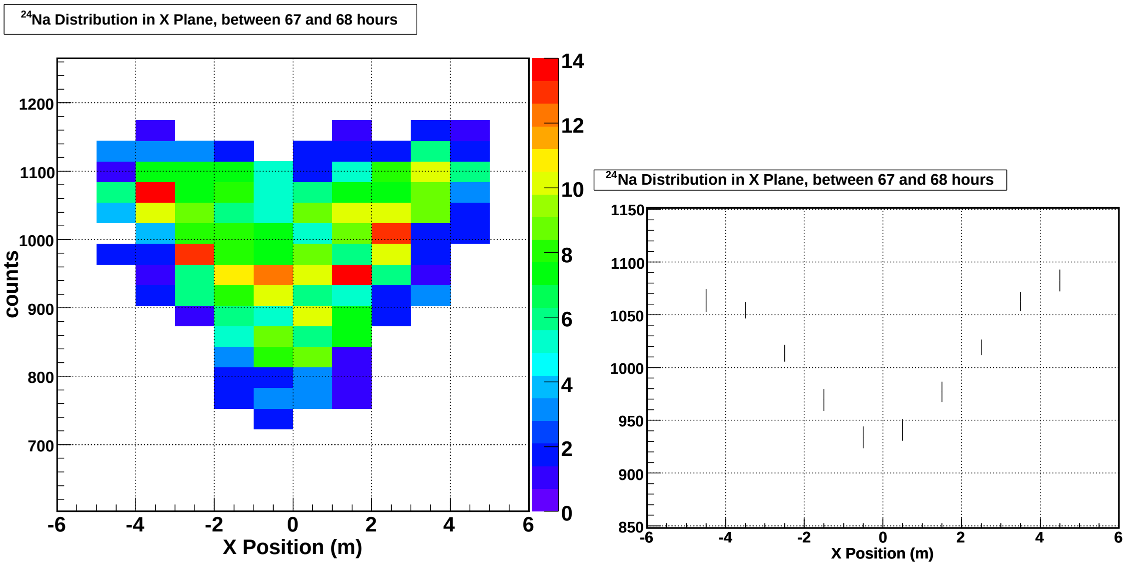


Figure 6.7: The left plot is the x distribution of Mixed Activity. The right is a profile of the left, where the points are the average values and the error bars are the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

When looking along the z-direction, in Figure 6.10, we see a large deficit in the high z-position region. We don't expect the z-distribution to follow the same as x, y or ρ, because the detector is not symmetric with those directions. The deficit at high z-position is be caused by a number of reasons. The neck drops below the 600 cm radius of the AV. this creates an extra portion of acrylic where the neutrons can capture. The neck is also filled with D_2O instead of H_2O which surrounds the rest of the AV. There are also very few PMTs in the neck causing difficulties in high z-position event reconstruction.

Using a Monte Carlo calculation of uniformly distributed ^{24}Na, we can see in

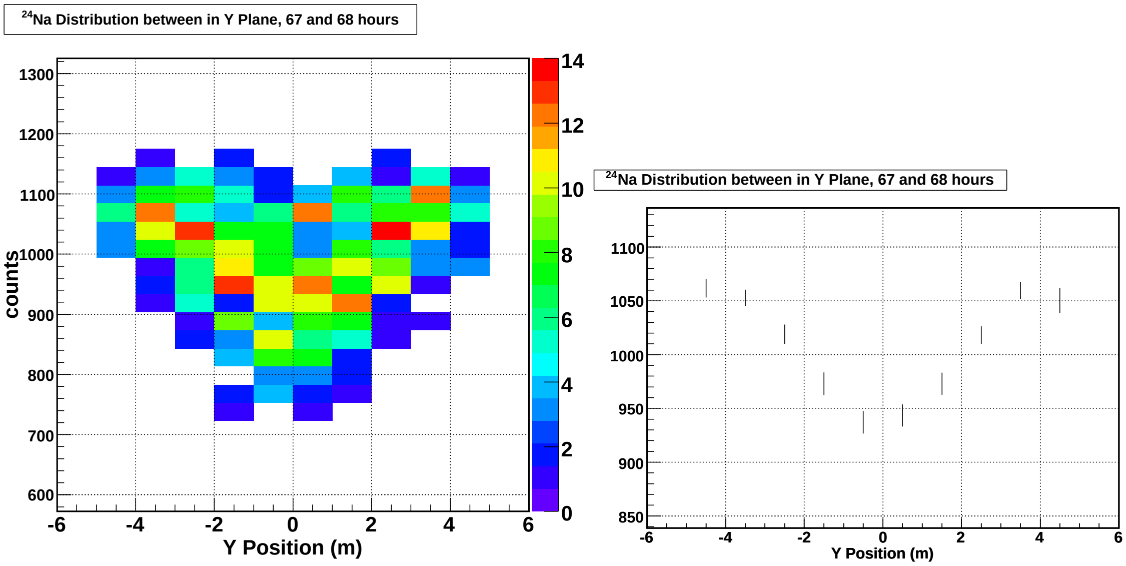


Figure 6.8: The left plot is the y distribution of Mixed Activity. The right is a profile of the left, where the points are the average values and the error bars are the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

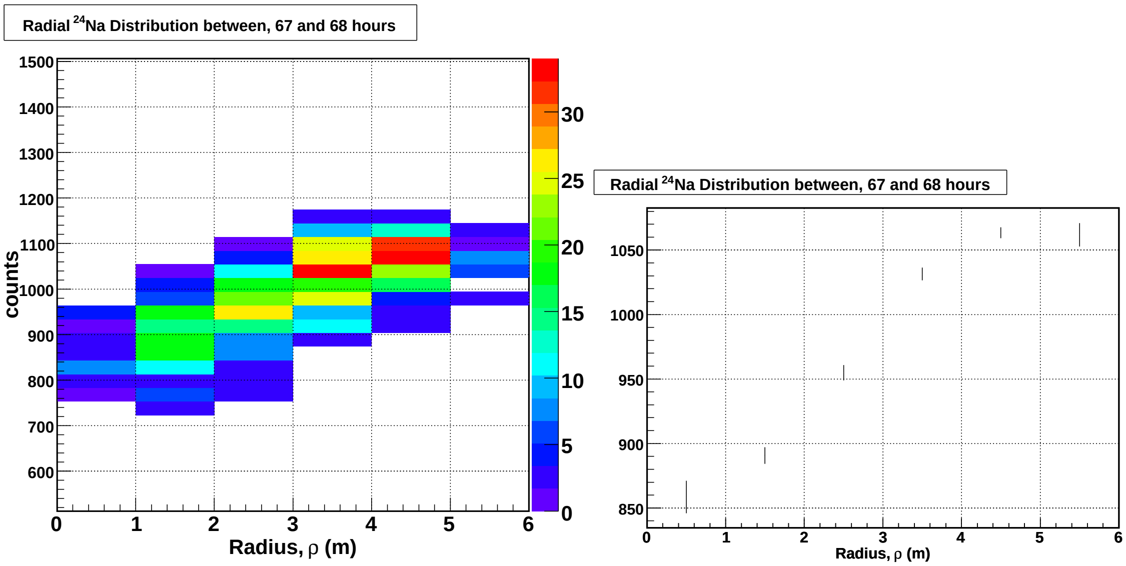


Figure 6.9: The left plot is the radial distribution of Mixed Activity. The right is a profile of the left, where the points are the average values and the error bars are the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

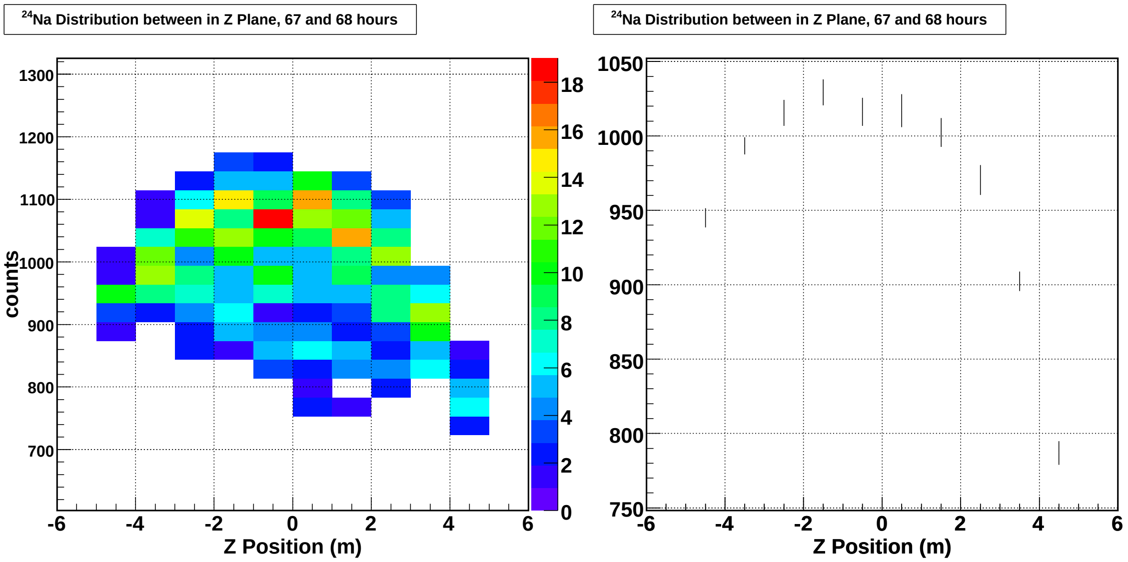


Figure 6.10: The left plot is the z distribution of Mixed Activity. The right is a profile of the left, where the points are the average values and the error bars are the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

Figure 6.11 that there is still a lower activity seen in the centre of SNO. This is also seen in Figure 6.12, and in Figure 6.13. The Monte Carlo calculation supports the shadowing effect from the NCDs.

Looking at Figure 6.14, we see the same drop off as in Figure 6.10. This supports the conclusions that there are many neutrons being absorbed outside of the 600 cm radius or in the acrylic and not seen.

6.1.3 *Trigger Thresholds During Mixing*

As the mixing was taking place the trigger thresholds had to be raised, as discussed in Section 3.2. As the ^{24}Na decayed, the thresholds were gradually being brought down. The progression can be found in Table 6.1. The threshold is the setting of the trigger, N100_med, which fires when the specified number of PMTs (listed in Table

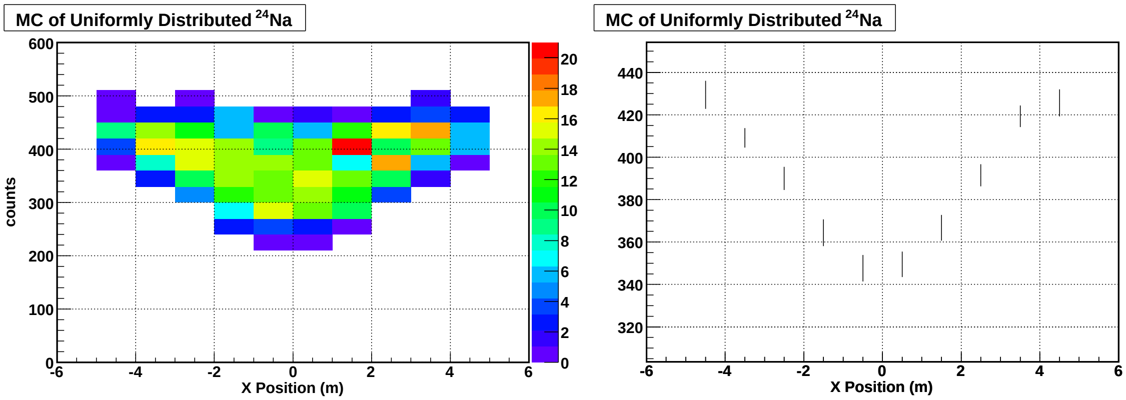


Figure 6.11: The left plot is the Monte Carlo of the X distribution of Mixed Activity. The right is a profile of the left, where the points are the average values and the error bars are the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

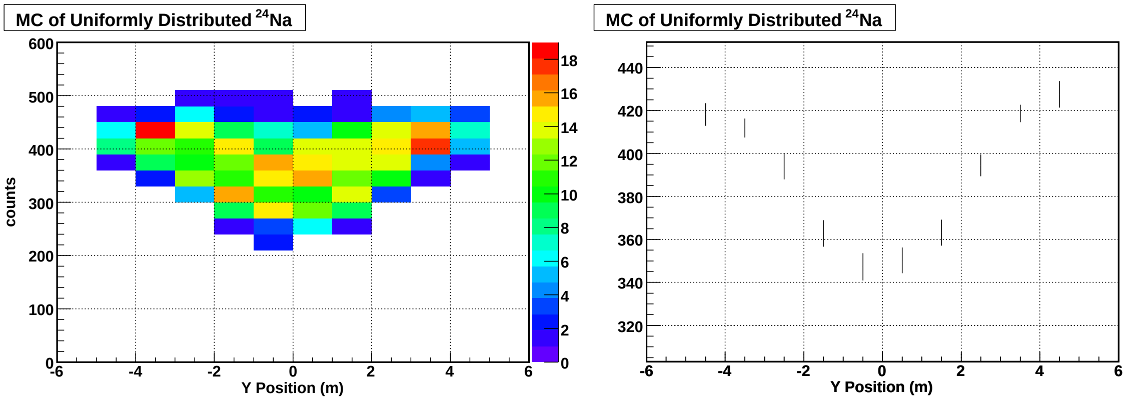


Figure 6.12: The left plot is the Monte Carlo of the Y distribution of Mixed Activity. The right is a profile of the left, where the points are the average values and the error bars are the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

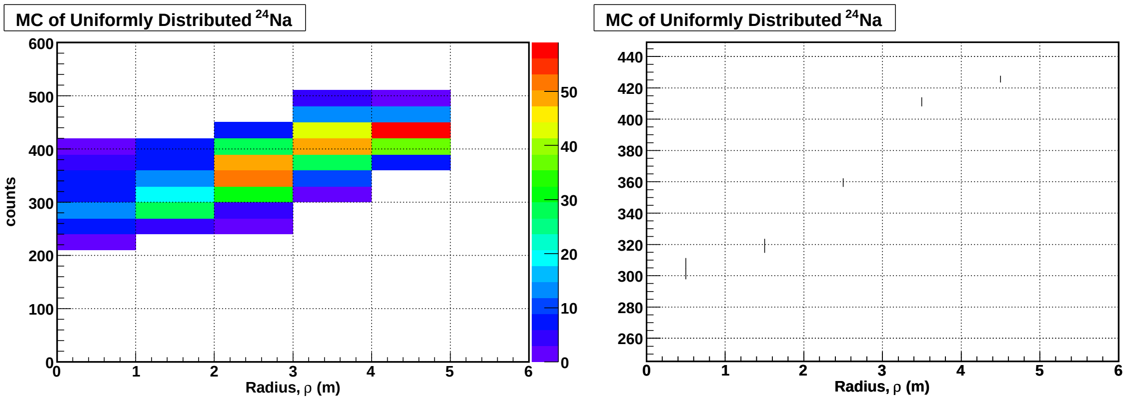


Figure 6.13: The left plot is the Monte Carlo of the radial distribution of Mixed Activity. The right is a profile of the left, where the points are the average values and the error bars are the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

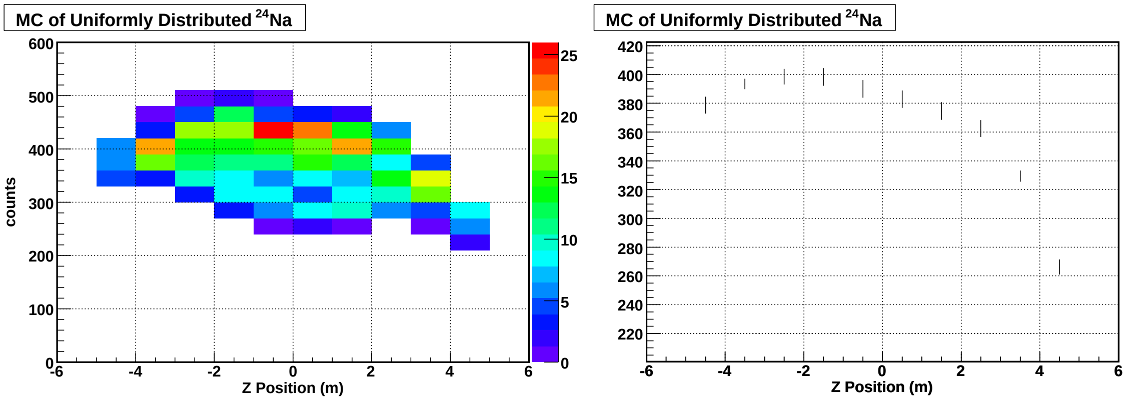


Figure 6.14: The left plot is the Monte Carlo of the Z distribution of Mixed Activity. The right is a profile of the left, where the error bars are the points are the average values and the standard deviation of the distribution. The colour scale is the number of cubes in that bin.

Date	Run	N100_med	N100_hi	N20	Comments
14:56Oct 4	55786	33	37	25.5	
23:30 Oct 4	55798	32	36	24.5	
08:31 Oct 5	55803	31	35	23.5	
10:42 Oct 5	55804	30	34	22.5	
15:55 Oct 5	55811	29	33	21.5	
20:57 Oct 5	55818	28	32	20.5	
00:09 Oct 6	55822	27	31	19.5	
05:47 Oct6	55830	26	30	18.5	
09:30 Oct 6	55835	24	28	17.5	
14:33 Oct 6	55840	23	27	17.5	
20:55 Oct 6	55849	22	26	16.5	
02:42 Oct 7	55857	21	25	16.5	
06:56 Oct 7	55864	20	24	16.5	
09:02 Oct 7	55867	18	22	15.5	
09:45 Oct 7	55868	17	21	14.5	
11:54 Oct 7	55871	16	20	13.5	
12:38 Oct 7	55872	15	19	12.5	PMT rate higher than usual ~400 Hz

Table 6.1: Changing thresholds throughout the mixing of the radioactive brine.

6.1) fire within a time window of 100 ns. The N100_hi trigger fires when the specified number of PMTs, always higher than the N100_med trigger, (listed in Table 6.1) fire within a 100 ns window. The N20 threshold is the same as the previous two, but the PMTs must be triggered in a 20 ns window. The higher thresholds reduce the number of events we can see regardless of where the event occurred.

6.2 Decay Time

As of 12:00 Friday, October 7th, 2005 the ^{24}Na was mixed and this was considered the start of the mixed data set. As with all radioactive sources we know that ^{24}Na will decay. The time it takes to decay will follow equation 3.1.

$$A(t) = A_0 e^{-\lambda t} \tag{6.3}$$

The variables are the same as those in section 3.1.

Work has been done to calculate the neutron rate as seen in the NCDs, and to develop an understanding of the systematic error. This work is on going and very near completion. The calculations of the rate here are taken from the work in progress(17). The equation for the neutron rate is:

$$R_{neu} = \frac{1}{LT_{clock}\epsilon_{dc}^{PMT} LF_m \epsilon_{dc}^{sc}} \sum_{strings} \left(\frac{N_{mux} \left(\frac{N_{sc}^{good}}{N_{sc}} \right)}{\epsilon_{capt}\epsilon_T^{mux}\epsilon_T^{sc}} \right) \tag{6.4}$$

where LT_{clock} is the total livetime as measured by the scalers, and corrected for the basic cleaning cuts. ϵ_{dc}^{PMT}, ϵ_{dc}^{sc} are the corrections for the deadtime due to the PMTs, and shapers respectively. LF_m is the livetime fraction from the MUX's. N_{sc} is the number of shaper events, N_{sc}^{good} is the number of good shaper events (those which have a scope trace). N_{mux} is the number of MUX events. ϵ_{capt} in the capture efficiency, and ϵ_T^{sc}, ϵ_T^{mux} are the shaper and MUX threshold efficiencies.

To make Figure 6.15, a modified version of equation 6.4 was used. The substitution in equation 6.5 was made:

$$\sum_{strings} N_{mux} \left(\frac{N_{sc}^{good}}{N_{sc}} \right) = \sum_{strings} \frac{N_{sc}^{good}}{LF_{sc}} \tag{6.5}$$

where LF_{sc} is the livetime fraction of the shapers. For a detailed derivation of these equations, see (17).

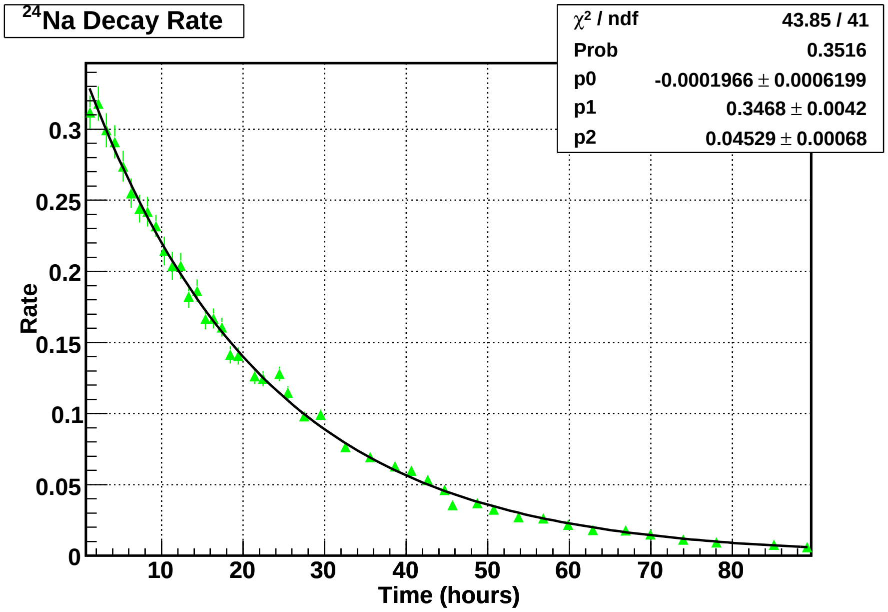


Figure 6.15: ^{24}Na decay over time of mixed data set using the NCD array.

Figure 6.15 shows the measured decay rate as a function of time, using equation 6.4. It was fit to equation 6.6, which follows from equation 3.1, allowing the decay rate to vary.

$$R = p0 + p1e^{-p2\ x} \tag{6.6}$$

$p0$ is a flat background, $p1$ is the amplitude, $p2$ is the decay constant (h^{-1}), x is time in hours and $\frac{ln(2)}{p2}$ is the halflife.

This fit gives a value of 15.30 ± 0.23 hours for the halflife which is consistent at the 1.5 σ level with value given in Figure 2.3, of 14.959 hours.

6.3 ^{24}Na Strength Determination

There are four methods used to find the strength of the injected brine. The two in-situ measurements use the central sealed ^{24}Na source and the PMT and NCD arrays. The two ex-situ measurements use germanium detectors. To compare these measurements to each other, a reference date of 09:00 September 28, 2005 has been chosen. This is the date of the actual activation of the sodium sample.

6.3.1 ^{24}Na Strength as determined by the Guelph Germanium Detector

The germanium detector is described in Section 3.6.3. A 30.44 ± 0.02 g sample was taken before the ^{24}Na was injected into the active volume, and sent to Guelph to determine the strength of the injected sample. The exact calibration of the apparatus is still being determined.

The results that have been obtained from Guelph to date indicate a source strength of 449 ± 5 Bq as of 12:00 October 4, 2005. The quoted error on this term is only statistical. This has then been corrected for absorption effects in the source and in the calibration source. The estimate of the error in the calibration source strength is about 5%. Since there was 968.7 g of brine injected, the strength of the injected sample was 14290 ± 720 Bq.

At the reference date the strength is 12.7 ± 0.6 MBq. To get the rate in neutrons per second we divide by 380 (one in 380 gamma-rays photo-disintegrate a deuteron). This gives a reference activity of 33500 ± 1700 n/s.

6.3.2 ^{24}Na Strength as Determined by the Underground Germanium Detector

The germanium detector underground was described in Section 3.6.2. It was given a sample of 30.63 ± 0.02 g at the time of the ^{24}Na brine injection. The analysis of this sample, and scaling the results to the injected volume of 968.7 g, shows that the strength was 479 ± 19 Bq at 12:37 October 7, 2005. At the reference date, the activity was 12.5 ± 0.5 MBq. Converting to neutrons per second that is 32400 ± 1300 n/s.

6.3.3 ^{24}Na Strength as Determined by the Central Canned Source Compared to the ^{252}Cf Using the PMT Array

In Section 4.7.2, it was explained that the ^{252}Cf was deployed in the center of the volume only three days before a sealed ^{24}Na sample weighing 10.36 g was placed in the same location. The ^{252}Cf source strength has been accurately measured as 16.55 ± 0.08 n/s on June 12, 2001, and thus its strength at any time can be calculated easily by using equation 6.3. The ^{252}Cf source was deployed for 3 hours 38 minutes, and the central delrin can of ^{24}Na brine was deployed for 19 hours 40 minutes.

When neutrons capture on deuterium, they emit 6.1 MeV gamma-ray that produce Cerenkov light in the D_2O. If we plot the NHIT for many events, we obtain an NHIT spectrum(18). The ratio of events is the same as the ratio of analyzed neutrons. Comparing the NHIT spectrum of ^{24}Na to ^{252}Cf, as shown in Figure 6.16, we can get the strength of ^{24}Na as a ratio to ^{252}Cf. This ratio is shown for run 55758 in Figure 6.17. Such a ratio was made for all five central can runs. The ratio was determined for each run and plotted as a function of time in Figure 6.18.

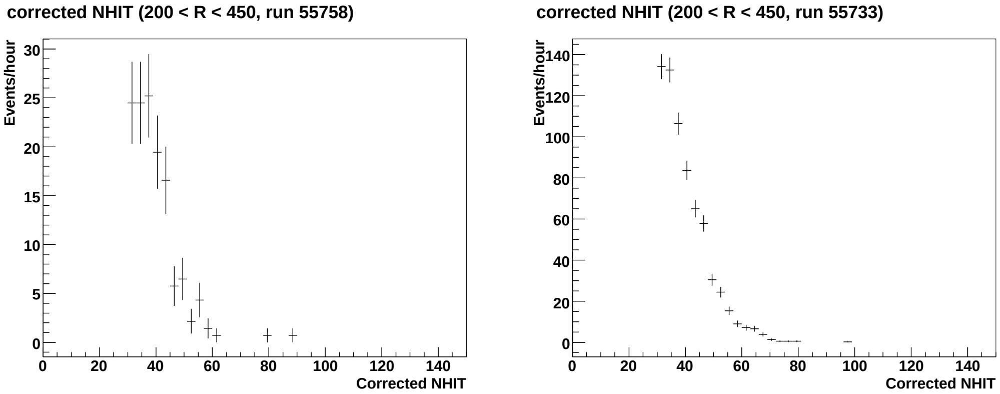


Figure 6.16: Example of NHIT spectrum comparison between ^{24}Na run (55758) and ^{252}Cf run (55733).

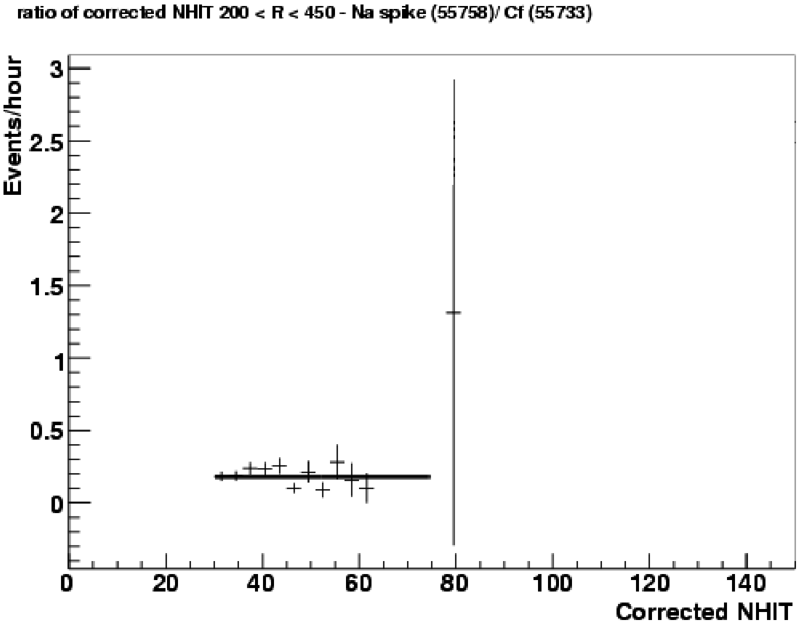


Figure 6.17: Comparison of ^{24}Na to ^{252}Cf central encapsulated source runs to obtain the ^{24}Na strength.

In Figure 6.18, the ratio of the ^{24}Na to the ^{252}Cf source strengths is shown on a

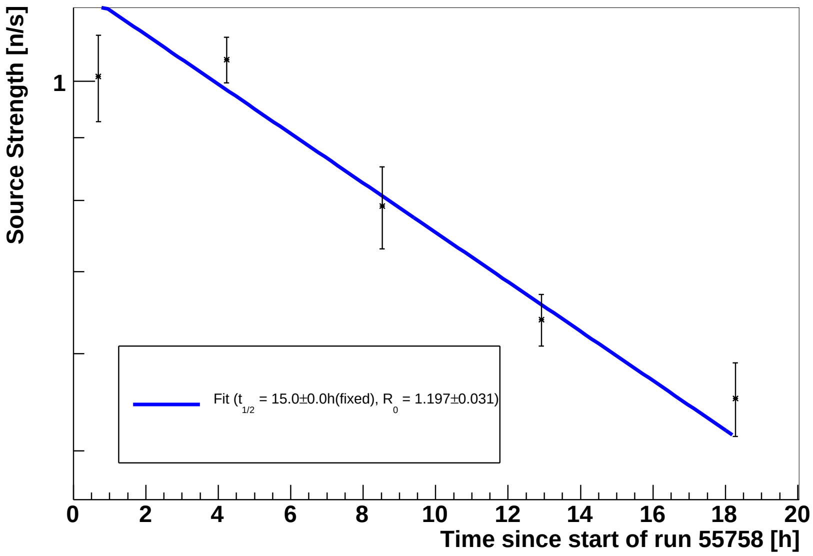


Figure 6.18: Measurement of the rate of neutrons from ^{24}Na source run.

log scale. To calculate the strength at the time of the deployment of the delrin can, the decay rate of the ^{24}Na has been fixed to 15.00 hours in the fit to equation 6.7.

$$ln(\frac{R(t)}{R_0}) = -\lambda t \tag{6.7}$$

where R is the rate of decay, at time t, and R_0 is the rate (or source strength) at $t = 0$.

If the fit is extrapolated to the start of comparison at 11:39:05 October 3, 2005 the rate is $R_0 = 1.197 \pm 0.031$ neutrons/second. To calculate the activity at the reference date we use equation 6.8

$$A_{Ref} = R_0 e^{\lambda t} \frac{V_{injected}}{V_{sample}} \frac{R_{sample}}{R_{Cf}} A_{Cf} \delta \tag{6.8}$$

At the reference date, we get a strength of $R_0 e^{\lambda t} = 353 \pm 9$ n/s. Since this is for the $V_{sample} = 10.36 \pm 0.01$ g sample, and the injected sample is, $V_{injected} = 968.7 \pm 0.1$

g, this strength must be scaled by 93.5 to get the activity for the total injected volume. The result is a rate of 33000 ± 850 n/s. This number must be corrected by a factor of $\delta = 1.0392 \pm 0.0075$. The correction factor was calculated by a MC simulation and is a result of the slightly different geometry and neutron capture cross sections for the two sources. The ratio of the ^{24}Na sample strength to the ^{252}Cf is, $\frac{R_{sample}}{R_{Cf}} = 0.179 \pm 0.014$ from Figure 6.17. The activity of the ^{252}Cf on September 28, 2005 was $A_{Cf} = 5.511 \pm 0.040$ n/s.

The total rate of the activated, injected brine, at the reference date, is then $A_{Ref} = 34300 \pm 920$ n/s.

6.3.4 ^{24}Na Strength as Determined by the Central Canned Source Compared to the ^{252}Cf Using the NCD Array

The same delrin canister that was compared to the ^{252}Cf in Section 6.3.3 using the PMT array can also be compared to the ^{252}Cf using the NCD array. These measurement are currently being analyzed and only preliminary numbers are available. The NCD array only measures the neutron flux, and the current strength estimate is 32400 ± 1300 n/s at the reference date.

6.3.5 ^{24}Na Strength Summary

The ^{24}Na strength was measured using four detectors. Two in-situ detectors, SNO's PMT array and SNO's NCD array, and two ex-situ detectors: a germanium detector located underground in the SNO facility and one at Guelph University. All of the strengths of the various samples were measured, then extrapolated back to a common

Detector	Strength (n/s)	Uncertainty (n/s)
SNO PMT	34300	920
SNO NCD	32400	1300
U/G Ge	32400	1300
Guelph GE	33500	1700

Table 6.2: A Summary of the measured strengths of the injected ^{24}Na at a reference date of 09:00 September 28, 2005.

reference date of 09:00 September 28, 2005. Table 6.2 summarizes all the results. All strengths agree within their uncertainties. The average of the three completed strengths is 33600 ± 690 neutrons/second, or 12.8 ± 0.3 MBq. This is a weighted average, calculated using equation 6.9.

$$\bar{x} \pm \delta\bar{x} = \frac{\sum_i w_i x_i}{\sum_i w_i} \pm \left(\sum_i w_i\right)^{-\frac{1}{2}} \tag{6.9}$$

where $\bar{x}$ is the weighted average, $\delta\bar{x}$ is the uncertainty in the average, and $w_i = \frac{1}{(\delta x_i)^2}$.

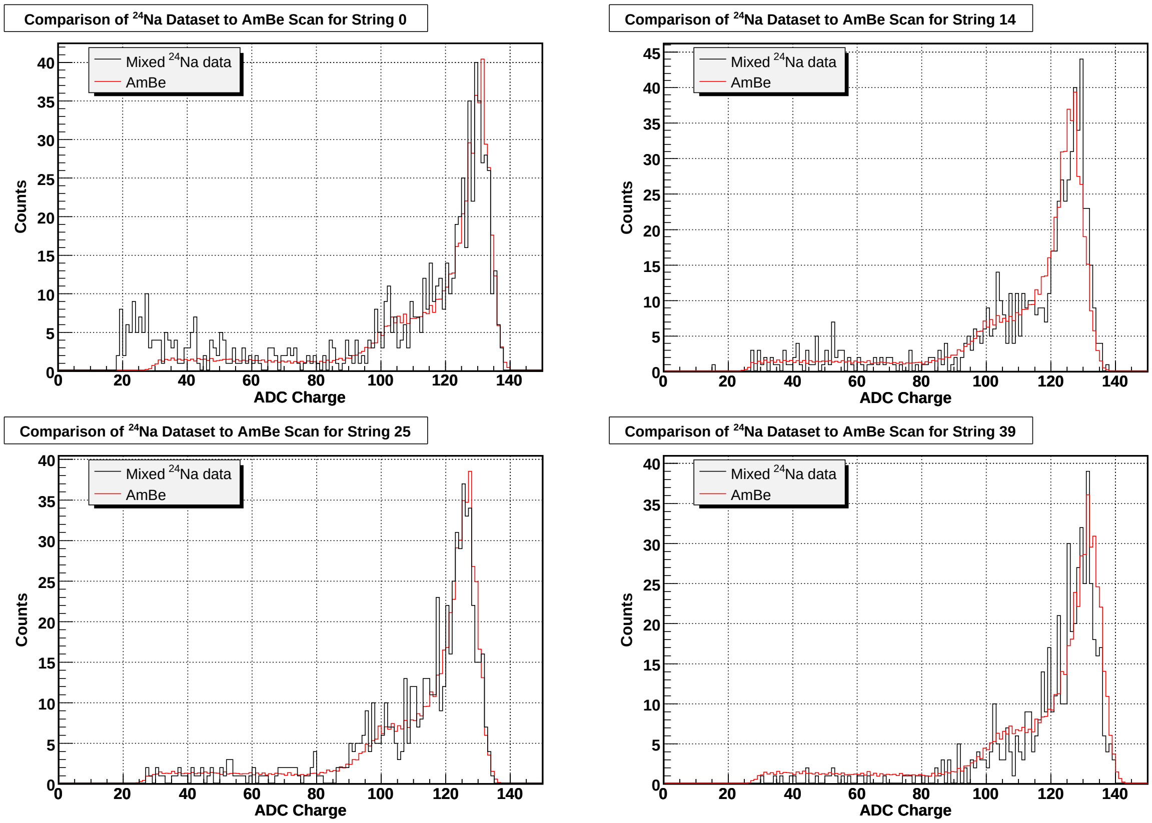
6.4 Comparing the ADC Charge Spectrum between ^{24}Na and AmBe

6.4.1 String to String Shape Comparison

The ^{24}Na is uniformly distributed in the active volume. This means that each ^{3}He string in the NCD array should detect the same number of neutrons per unit length. That is, as long as we ignore the neutrons that are captured in the light water and in the acrylic. When comparing from string to string, we must remember that each string is unique. That is the overall array efficiency should drop as a function of the radius as shown in Figure 2.1. Symmetrical strings, that is strings the same distance from the center, should be the same except for individual threshold effects and defects.

Each NCD event produces an ADC charge. Looking at this charge for multiple events gives the charge spectrum for that NCD. In the ADC charge spectrum, the peak corresponds to events in which the full energy of the proton and triton are deposited in the gas of the ^{3}He detector. If either hits the wall, less energy is seen. Since there are many positions and directions, there is a long low energy tail. The 'hump' before the peak is due to a build up effect on the anode. The proton and triton ionize the gas creating electrons. These electrons drift to the anode, but do not simultaneously arrive at the anode. As they travel to the anode, they ionize more gas causing more electrons. This cascade of electrons causes an electric field to build up around the anode. This field causes the following electrons to appear to have less charge. This shifts some apparent energy lower, out of the peak region causing the 'hump'. This effect is called 'space charge.'

To ensure that the ^{24}Na data is consistent with other neutron data, it was compared to data taken after an AmBe calibration source was in place. The AmBe source produces manly neutrons and so its ADC spectrum should match that of the ^{24}Na for each string since by the time the neutron reaches an NCD the neutron would be thermal. During the AmBe calibration scans the source is placed in many positions throughout the active volume. This makes the extrapolation of the results easier and a more fair comparison to the distributed ^{24}Na source. The ADC spectrum was compared for the 4 inner most strings (the N-strings), as shown in Figure 6.19.



Comparison of ^{24}Na Dataset to AmBe Scan for String 0

Comparison of ^{24}Na Dataset to AmBe Scan for String 14

Comparison of ^{24}Na Dataset to AmBe Scan for String 25

Comparison of ^{24}Na Dataset to AmBe Scan for String 39

Figure 6.19: AmBe compared to the ^{24}Na mixed dataset.

The AmBe and the ^{24}Na ADC spectra were compared using a 'pull' test, as defined by equation 6.10. This is a similar comparison as a χ^2 test, but keeps track of point by point differences between the two spectra, including the sign. A large deviation from zero in this test means that this bin has a disagreement between the two data sets. The 'pull' test assumes $\sigma = \sqrt{N}$, thus is only good for bins with large N.

$$\chi = \frac{F_1 D_1 - F_2 D_2}{F_1^2 D_1 + F_2^2 D_2 + \epsilon} \tag{6.10}$$

In equation 6.10, D_i is the number of counts in the bin for data set i and F_i is a normalizing factor for data set i. The denominator is the combined statistical error for the two data sets. ϵ is a small number to prevent the denominator from reaching zero.

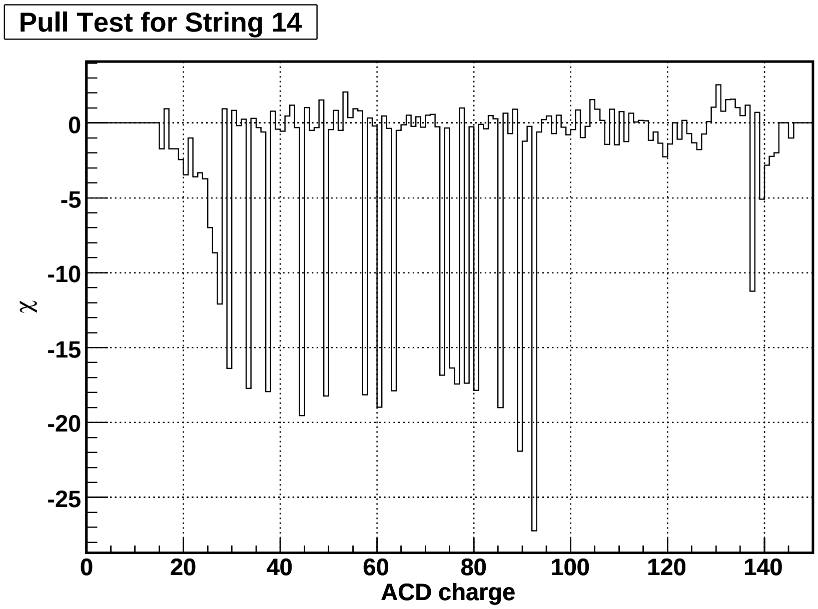


Figure 6.20: Example of pull test for AmBe and ^{24}Na.

Figure 6.20 shows an example of the pull test for ^{24}Na and AmBe data. Figure

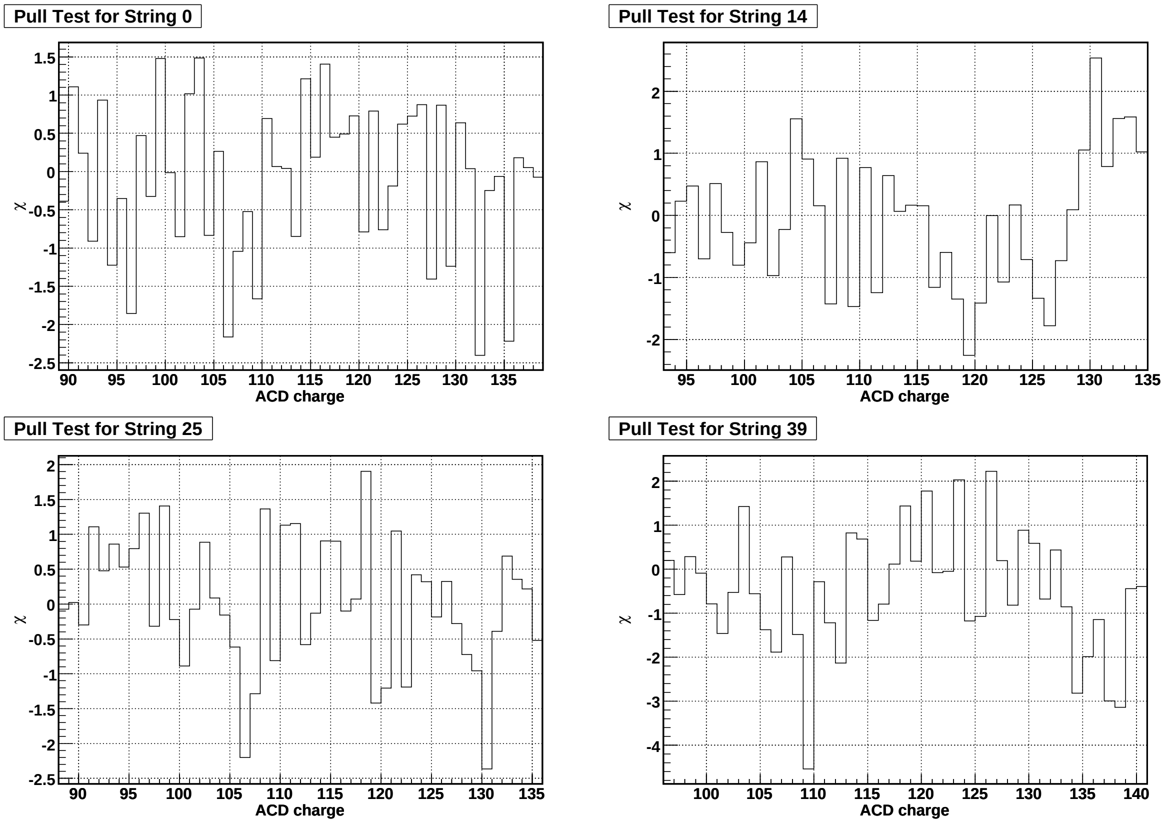


Figure 6.21: Pull tests for high statistic region in ADC charge spectrum.

6.21 shows the pull test results for just the statistically relevant region for each N-String. Since χ averages out to be approximately zero, the ADC charge spectrum of the ^{24}Na and AmBe are consistent.

In the ADC charge region 130-140 in Figure 6.20 it can be seen that there is an offset in the peak positions of the ADC spectra between the AmBe runs and the ^{24}Na data, this is explained in Section 6.4.2. Another feature is that there are large pulls in the lower ADC charge region of the spectrum. This is not due to a significant difference, but to the lack of statistics (low N) in the lower ADC region in the ^{24}Na data. To properly examine the low statistics region in the ADC spectrum, it was compared and treated as a Poisson distribution. Equation 6.11 shows the probability that we observe n counts if the expected number of counts is ν.

$$P_\nu(n) = \frac{\nu^n e^{-\nu}}{n!} A \tag{6.11}$$

n is the number of counts in a bin (in this case, the number of counts with a specific ADC charge), ν is the expected mean of the distribution, obtained from fitting a straight line to the AmBe data set in the low energy range (30 to 80). A is a scaling factor which matches the peak height of the Poisson distribution to the peak height of the ^{24}Na data. The peak height is determined by the number of bins in the region which have n counts.

By comparing the low charge regions of strings 14 and 25 to equation 6.11, we see that the both of these strings follow the Poisson distribution (Figure 6.22). This means that the low ADC charge regions between the ^{24}Na and AmBe source agree.

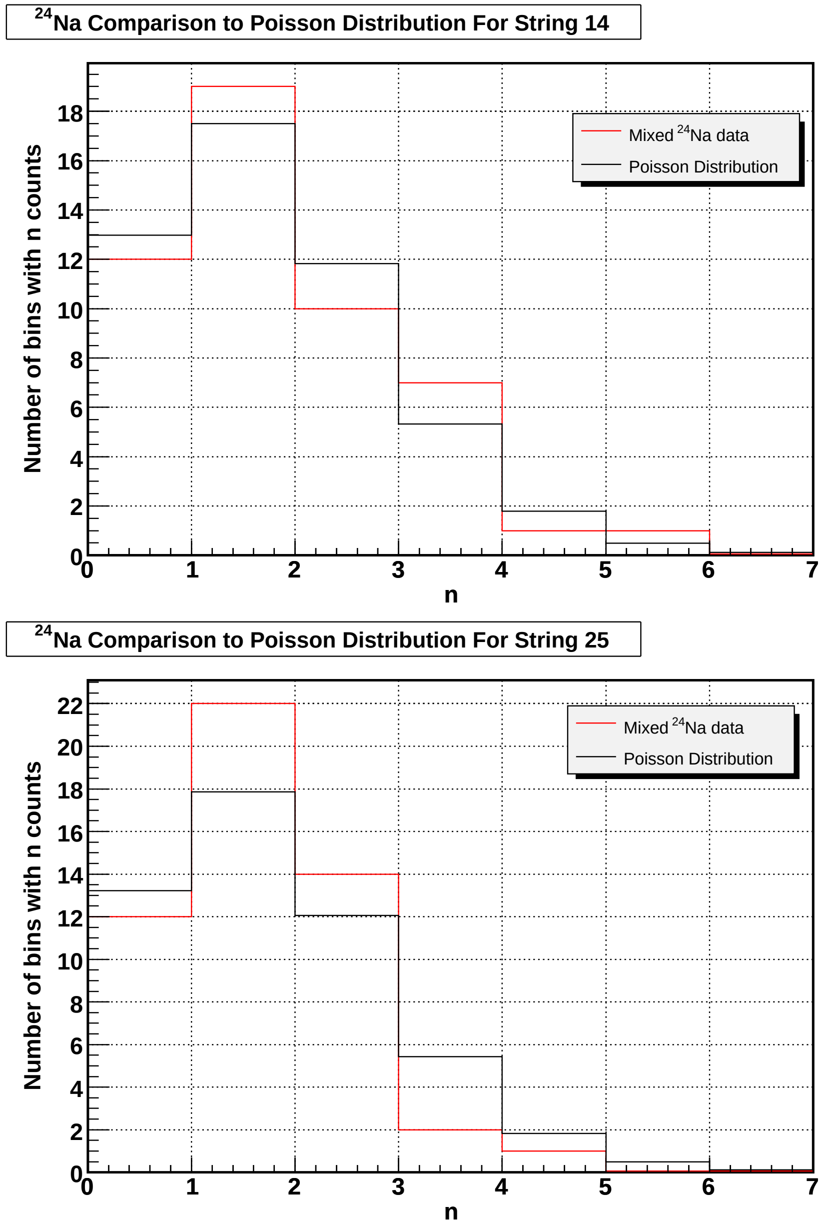


Figure 6.22: Lower ADC charge region from ^{24}Na data compared to a Poisson distribution for strings 14 and 25.

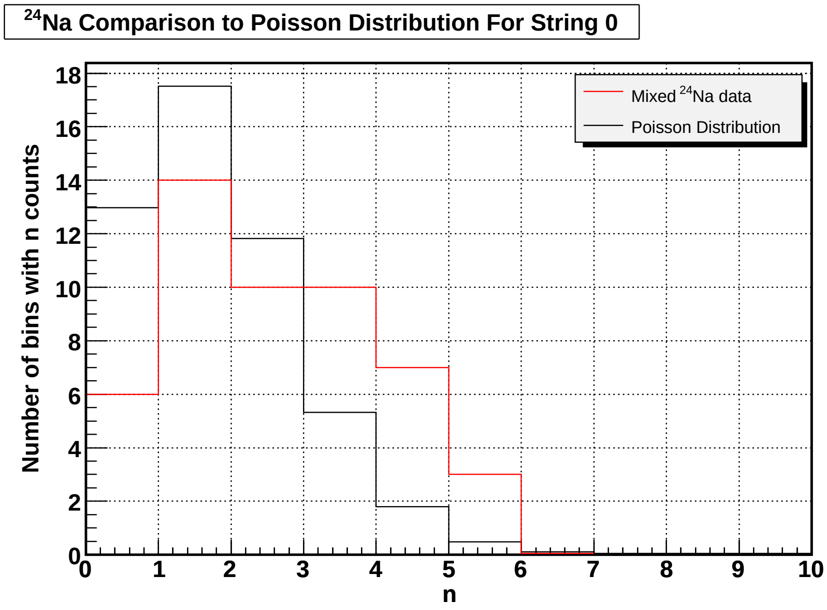


Figure 6.23: Lower ADC charge region from ^{24}Na data compared to a Poisson distribution for string 0.

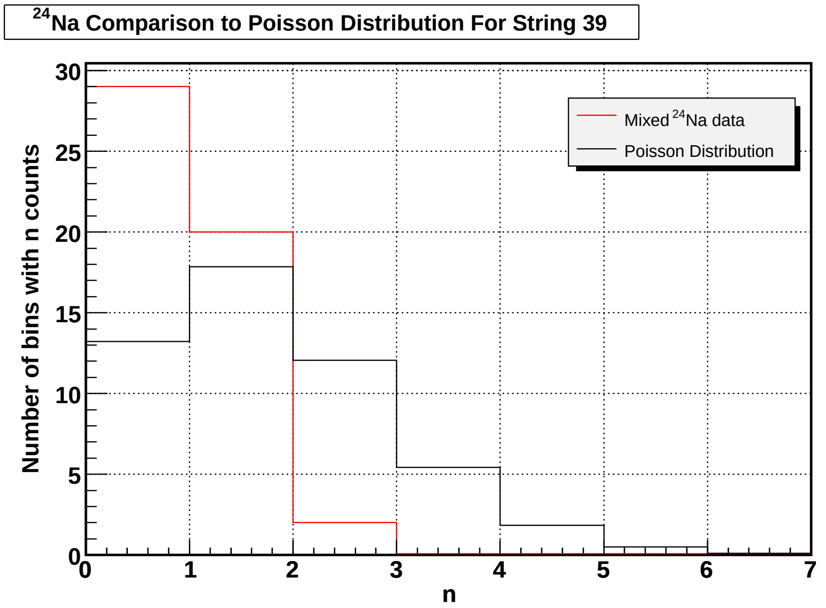


Figure 6.24: Lower ADC charge region from ^{24}Na data compared to a Poisson distribution for string 39.

It can be seen in Figure 6.23 that there are too many counts in the $n = 0$ bin for the ^{24}Na data for string 0. This is due to a raised MUX threshold during the ^{24}Na data collection period. The raised threshold reduces the amount of low charge events that trigger the ADC so there are many more low charge bins with zero events.

In Figure 6.24 we can see that in string 39 the ^{24}Na is too wide when compared to the Poisson distribution. This is due to the excess of noise in the lower charge region. This noise is unexplained at this point. Further studies are underway using data cleaning cuts to examine the pulses from these points.

6.4.2 Evidence of Gain Change from Counter to Counter in the NCD N-Strings

As seen in Figure 6.20, there seemed to be an offset in the peak of the ADC charge spectrum. A possible situation that would cause this would be if the individual ^{3}He neutron counters, in a given string, were each set at a different gain. As the source is moved, the relative contribution of different counters in the string to the overall capture rate changes, and counter to counter differences can be observed.

In November 2005, during a routine AmBe calibration period, there were six positions measured along the z-axis. For each of these positions the ADC charge spectrum was created. A Gaussian distribution, as shown in equation 6.1, was fit to the peak, and the mean was taken to be the center of the peak. These mean values were recorded for each z-position, shown in Figure 6.25.

From Figure 6.25, it can be seen that no NCD has a difference of more then 5% between counters. This difference is enough to account for the movement in the peak

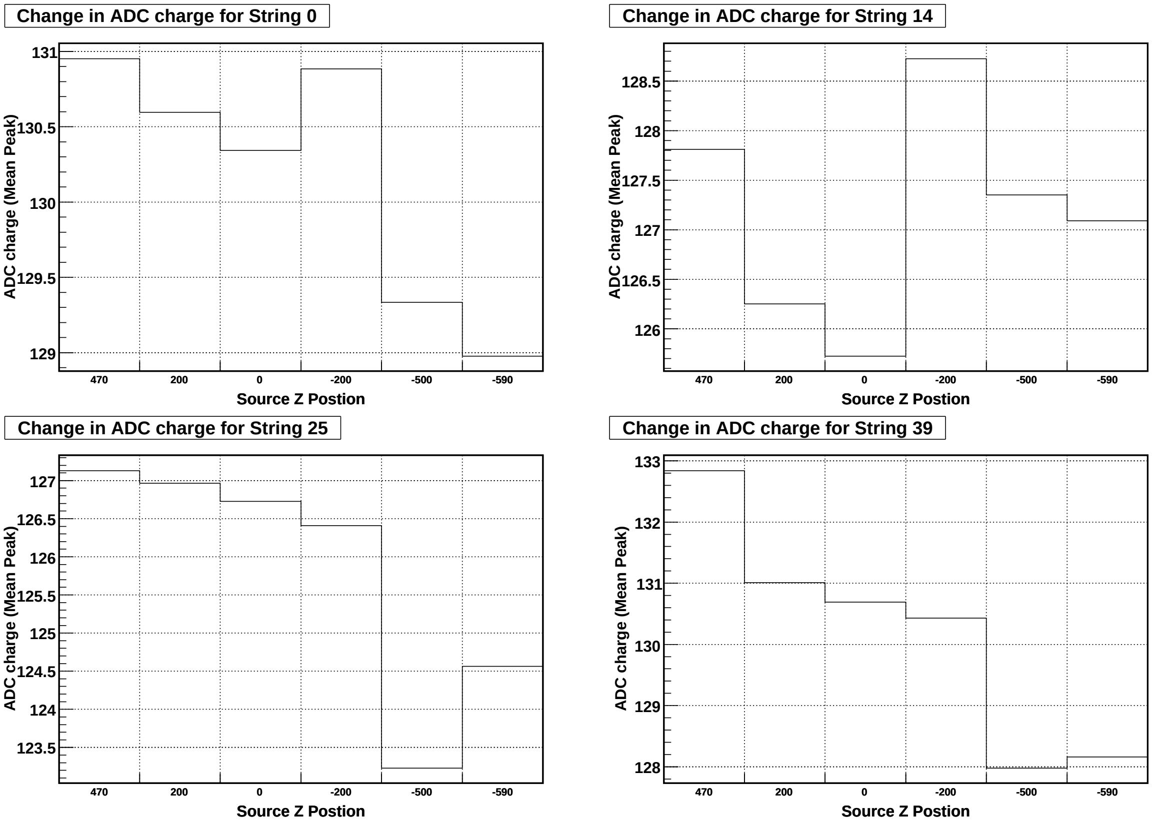


Figure 6.25: Changes in ADC charge peak position for AmBe scans at different Z-positions.

seen in Section 6.4.1.

Chapter 7. SUMMARY AND CONCLUSION

This is the first time a dispersed radioactive source has been injected into the active volume of the SNO to calibrate the NCDs. This experiment has proven to be a useful calibration in many areas of the flux analysis. It has been used in the determination of low energy backgrounds, NCD livetime calculations and as a means to get an absolute neutron detection efficiency. These are necessary steps in determining a neutrino flux using the NCDs.

An efficient and effective calibration procedure has been developed and explained in detail. This procedure includes the design and testing of the injection system, the injection plan and the precautions that were tested, and that had arisen throughout the experiment. It also explained the means of production, and transport of a ^{24}Na source. Precautions for how to handle the open source and prevent any outside contaminates from being introduced into the SNO detector were developed.

The ^{24}Na was shown to be mixed after 65 hours. This prediction verified previous models of D_2O motion in the AV (11). We were able to show that the activity settled to the bottom, swirled around the outside and eventually into the middle.

The decay of the injected ^{24}Na is the same rate as predicted from its halflife. This verifies our deadtime calculation, since the rate drop from much higher than normal neutrino running to essentially the same. The small differences that remain are attributed to many details of the efficiencies and livetime determinations of the NCD array and its associated electronics. The consistency between the decay rate and the known ^{24}Na halflife is a final test that shows that these numbers are understood.

The ^{23}Na was activated to ^{24}Na on September 28, 2005. At this time it had a strength of 12.70 ± 0.49 MBq. Two in-situ analysis of the strength were done using a 10 ml sample in a double sealed delrin canaster placed in the center of the SNO detector. The first was using the PMT array the second is using the NCD array. The analysis was not complete using the NCD array due to the same unknown efficiencies that arose when examining the ^{24}Na decay. The PMT array gave a strength of 13.03 ± 0.35 MBq

There were two ex-situ measurements done as well using a germanium detector. A 30 ml sample was sent to Guelph University, a second 30 ml sample was placed on the detector underground in the SNO facility. These gave strengths of 12.74 ± 0.64 and 12.32 ± 0.49 MBq respectively. All three strengths are consistent.

It has been shown here that the ^{24}Na activity produces an ADC spectrum consistent with the AmBe neutron source, verifying the data was neutrons as expected. This test was done first as a sanity check on the data, but proved useful in examine effects such as the raised MUX threshold on N1 and low energy noise on N4. It also shows that the NCD array response is different for a uniformly distributed source then a point source. This is shown in the ADC charge spectrum peak offset between the two datasets. This has lead into work to use the AmBe source to do a counter to counter (different then a string to string) energy calibration.

This open source injection has allowed much to be learned about the SNO detector, specifically its NCD array. It also provides a method to obtain an overall efficiency of the NCD array and provide a confirmation to the existing monte carlo simulations.

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APPENDIX

SNO Monte Carlo Simulation

This description of the SNO Monte Carlo is taken directly from the SNO salt paper(19).

The **SNO M**onte Carlo and **an**alysis (SNOMAN) code is used for off-line analysis of the SNO data and provides an accurate model of the detector for simulating neutrino and background events. The Monte Carlo (MC) processor in SNOMAN provides processors for the generation of different classes of events, propagation of the primary particles and any secondary particles (such as Compton electrons) that are created, detection of the signal by the PMTs and simulation of the electronics response. With the exception of a few physics simulations (such as optical photon propagation), widely used packages such as EGS4 (20), MCNP (21) and FLUKA (22) are used in SNOMAN to provide accurate propagation of electromagnetic showers, neutrons, and hadrons.

Detailed models of all the detector components and calibration sources are implemented in SNOMAN. Generators for neutrino and calibration source signals, radioactive backgrounds and cosmic rays are also provided. Input parameters such as optical attenuation coefficients are determined from detector calibration. Calibration and detector parameters are input to SNOMAN and probability density functions

(PDFs), used in the neutrino analysis, are generated. These features allow a direct assessment of the systematic uncertainties in physics measurements by comparing the detector responses for various calibration sources with the predictions of SNOMAN.

For the analysis of SNO data, SNOMAN provides various processors to unpack the data, to provide charge and time calibration of the PMT hits for each event, to reconstruct event position and direction, and to estimate the event energy.