HALO-1kT prototype He-3 counters: background studies

by

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Abstract

The last supernova near our galaxy was in 1987. HALO-1kT will be a low background galactic Supernova detector. HALO- 1kT needs to have low backgrounds to detect a supernova on the far side of the galaxy. A big source of backgrounds is the planned 4.3 km of helium-3 proportional counters. My research tested the prototype proportional counters to ensure their backgrounds are low enough to avoid regular false positives. The first way of testing them was to take the 4 counters underground at SNOLAB to collect 3-4 months of data as well as a 2-day calibration run to see what the base background rate is. Two of the counters were then attached to electrostatic counters and counted to determine the background of the wall material. Those results showed emanation rates of 0.137 Hz to 0.811 Hz in the wall material. While that is clean, it is not clean enough to meet HALO-1kT background goals.

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List of Symbols and Abbreviations

CC	Charged Current
CCSN	Core-Collapse Supernova
CVD nickel	Chemical Vapour Deposition nickel
DAQ	Data Acquisition System
DOE	Department of Energy
DUNE	Deep Underground Neutrino Experiment
ESC	Electrostatic Counter
GADMC	Global Argon Dark Matter Collaboration
HALO	Helium and Lead Observatory
HALO-1kT	Helium and Lead Observatory 1 kilotonne
He-3	Helium 3
IBD	Inverse Beta Decay
JUNO	Jiangmen Underground Neutrino Observatory
KamiokaNDE	Kamioka Nucleon Decay Experiment
KamLAND	Kamioka Liquid Scintillator Anti-Neutrino Detector
LAND	Lead Astronomical Neutrino Detector
LEP	Large Electron-Positron Collider
LNGS	Laboratori Nazionali del Gran Sasso
$M_\odot$	One Solar Mass, unit, $2 \text{x} 10^{30}$ kg
m.w.e.	Meter water equivalent
NC	Neutral Current
NCD	Neutral Current Detector
PMT	Photomultiplier tube
ppb	Parts per billion
SN1987A	The 1987 core-collapse supernova
SNEWS	Supernova Early Warning System
SNO	Sudbury Neutrino Observatory
UPW	Ultra-Pure Water
WIMP	Weakly Interacting Massive Particles
Z	Atomic Number

Chapter 1

Introduction

Massive stars tend to end their lives in a supernova explosion. Physicists know a lot about how stars evolve and die, but there is always more that can be learnt. By studying supernovae physicists and astronomers can learn more about stars and the particles they create. When a star ends its life in a core-collapse supernova it releases a burst of neutrinos, that is, a very large amount of neutrinos get released from the star within ten seconds. If a core-collapse supernova takes place in our galaxy this burst of neutrinos can be detected by experiments on Earth. One of these supernova detectors is the Helium and Lead Observatory, HALO, that is operating in SNOLAB in Sudbury, Ontario. HALO has been operating since 2012 and is a prototype for a future detector, HALO-1kT.

HALO-1kT is planned to be built in the Laboratori Nazionali del Gran Sasso, LNGS, in Italy. It is currently in the components testing stage. As the names of the experiments implies HALO and HALO-1kT are experiments that use lead as a target for the supernova neutrinos and helium-3 neutron counters to detect neutrons produced from the neutrino-lead interactions. HALO-1kT will have 1 kT of lead as the target whereas HALO was constructed with 79 tonnes of lead. The burst of neutrons is moderated within the detector materials reduced to thermal energies where they are then effectively captured on the helium-3 and converted to electrical signals by the proportional counters. These electrical signals are digitized and recorded as data on a network.

As with many experiments that want to detect particles coming from space, HALO-1kT needs to have low backgrounds. Backgrounds refers to any ambient particles, or noise, which are unrelated to the supernova signal that the counters could pick up. Some backgrounds cannot be controlled, like the amount of neutrons in the lab at any given time, but there are backgrounds that can be minimized, like choosing the lowest background materials possible for the detector construction. As HALO-1kT is planned to have 4.3 km of helium-3 counters, they need to have as low backgrounds as possible.

There are many particle experiments sensitive to supernovae around the world. There are also many astronomers who want to see, with telescopes, the early stages of a supernova. These two groups have teamed up and formed a collaboration called the Supernova Early Warning System, SNEWS [1]. The main goal of SNEWS is to alert the astronomical community to a supernova promptly. The astronomers get an email alert when two or more experiments have a coincidence alarm. That is when two or more experiments detect what appears to be a supernova within ten seconds of each other. SNEWS has certain requirements in relation to backgrounds in order to minimize false positive alarms. Any burst identification software trigger will be satisfied by random coincident of background events if the background rate is high enough. This means any experiment that is part of SNEWS needs to make sure the backgrounds are low enough to avoid regular false positives.

In order to ensure low background rates before building the final detector, HALO-1kT ordered several commercial helium-3 neutron counters from two different companies. These counters were tested and found to have background rates that are about 100 times too high to meet the SNEWS false positive requirements. This thesis covers the testing of the commercial counters that took place to determine which parts of the counters the background is coming from and where it would be possible to minimize these backgrounds.

Chapter 2 is a discussion on supernovae, particularly why they are interesting and what might be learnt from them. It will also give a summary on the types of supernovae and core-collapse supernovae specifically.

Chapter 3 tells the history and discovery of the neutrino; explains why neutrinos are interesting; and finally will discuss the types of detectors used to detect neutrinos.

Chapter 4 describes the HALO-1kT detector, particularly why lead is used as a target and why and where this detector is being built.

Chapter 5 expands on the Super Nova Early Warning System, which HALO-1kT will be a part of when it is built and running. This chapter will also detail the background goals that HALO-1kT will need to meet to become part of the Supernova Early Warning System and see a supernova anywhere in this galaxy, as well as the various backgrounds that could be possible in HALO-1kT.

Chapter 6 explains the measurements of the backgrounds of several prototype counters, where the backgrounds are coming from, and how to improve the backgrounds to meet the set goals.

Chapter 7 is a discussion of the results and what can be done to reach the goals laid out for HALO-1kT to meet the Supernova Early Warning System goals.

Chapter 2

Supernovae

Why research supernovae? In the Universe there is a supernova approximately every second, in the Milky Way Galaxy there is a supernova approximately every 61+24/-14 years [2]. In the past 1000 years humans have only observed six supernovae in our galaxy. The last supernova that happened near this galaxy was in 1987, SN1987A, and was a core-collapse supernova that took place in the Large Magellanic Cloud, a satellite galaxy of the Milky Way. When SN1987A happened neutrino research was a fairly new field of physics research, there were no dedicated supernovae detectors and few neutrino detectors. Since 1987 neutrino research has come a long way and there are now dedicated supernova detectors as well as many more neutrino detectors with other primary physics goals around the world. Detecting how a star dies will provide a lot of interesting information about the universe, neutrinos, and stars; particularly interesting is how a massive star, that is a star at least eight times the mass of the sun, goes out with an explosion and how that explosion happens. These explosions are called supernovae, and there are two main types, which along with their subtypes are described in Section 2.2. Before getting into types of supernovae, how stars are formed, evolve, and go supernova will be discussed in Section 2.1.

2.1 Stellar Evolution

Stars start their lives as a dust cloud, inside the dust cloud there is turbulence causing a ball of gas and dust to form. Once this ball of gas and dust reaches a critical mass, the gravitational pull causes the dust cloud to collapse in on itself and the material in at the centre of the ball starts to heat up forming a protostar.

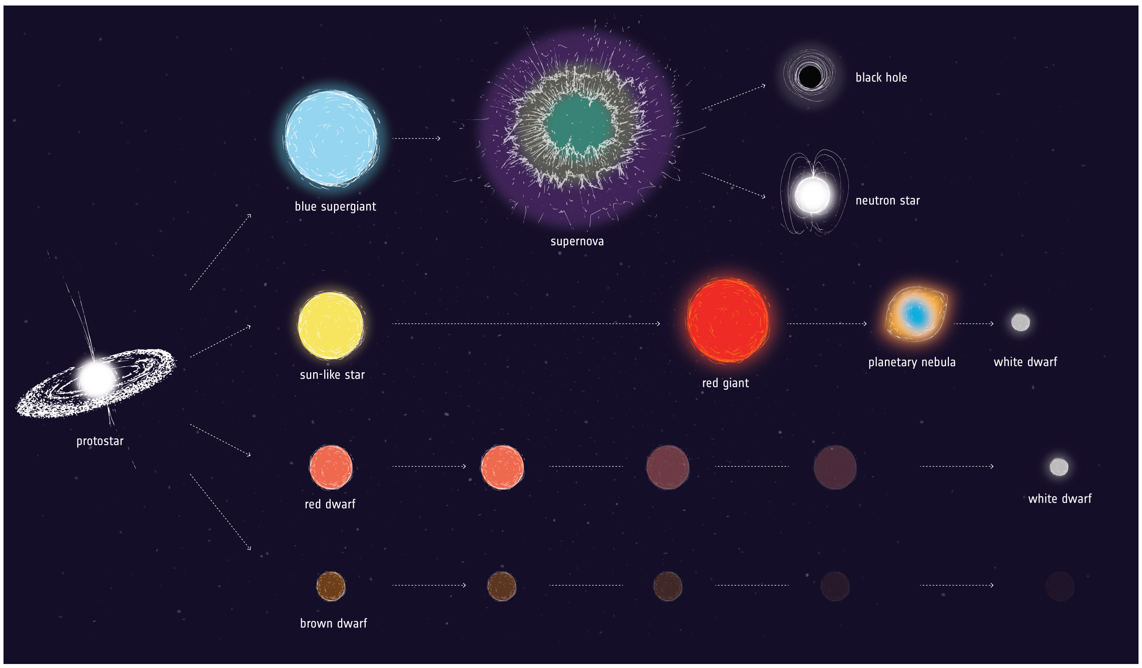

Figure 2.1: The various ways a star can evolve [3].

Once a protostar is formed there are several ways it can evolve, as shown in Figure 2.1. A solar mass, $M_\odot = 2\text{x}10^{30}$ kg, is a unit of mass approximately equal to the mass of the sun. A protostar that fails to turn into a star is called a brown dwarf, they fail because they are too small to reach the temperature required for thermonuclear fusion to begin. These failed stars are less than 0.08 $M_\odot$ and are mostly hydrogen but they have no internal energy source and emit almost no visible light. Stars larger than 0.08 $M_\odot$ but less than 0.8 $M_\odot$ are called red dwarfs. Red dwarf stars are the smallest and most common stars in the universe, glowing between 3000 K and 4000 K [4]. They are also the least luminous of mainline stars, i.e. stars that have stable thermonuclear fusion. Once red dwarfs burn through all their hydrogen, which takes approximately 14 billion years, they have no radiation pressure to counter gravity they fade and collapse leaving behind just the core, otherwise known as a white dwarf.

Next are sunlike stars, these stars start the same as the previous stars and they burn hot enough to fuse hydrogen into helium and counteract the gravitational force. This phase of a sunlike star will last about 10 billion years. Once all the hydrogen in a star's core has burned, the star stops having nuclear reactions. This causes the core to collapse on itself and become even hotter. The layers closest to the core also start collapsing and burning while the outer layers of the star at this point expand and cool causing the star to transform into a red giant as the star decreases in temperature and increases in brightness. A wind will sweep across a red giant taking the hydrogen and other elements around the centre core to the outside of the star forming a bubble of gas around the core called a planetary nebula. The planetary nebula expands into space and in about 50 000 years the nebula thins enough to leave behind the stars core, which is known as a white dwarf [5].

White dwarfs can go supernova under certain conditions. If the white dwarf is part of a binary star system it is possible for a white dwarf to pull matter from the other star, causing the white dwarf to increase its mass and become more dense. Once the white dwarf pulls sufficient matter from the other star it will reach a hot enough temperature to fuse carbon and oxygen via a flame starting at the core and spreading towards the outside, turning the carbon and oxygen into nickel. The flame part of the explosion only lasts a few seconds but the nickel left behind will decay and glow for several weeks [6]. This type of supernovae are called type Ia and will be discussed more in the following section.

Massive stars, in Figure 2.1 depicted by blue supergiants, start the same as sunlike stars, but are at least 8 $M_\odot$, these stars are the best candidates to go supernova. The first stage of a star going supernova for stars that have hydrogen is the fusion of hydrogen into helium in the star's core. A star develops onion-like layers of shells, the core being composed of iron or O-Ne-Mg, and the shells being composed of elements that have a smaller atomic weight at each subsequent shell towards the outermost, lightest shell of hydrogen. The general composition from the innermost layer to the outermost layer is: iron, silicon, oxygen, carbon, helium, then hydrogen. When there is no more hydrogen in the core of the star the hydrogen in the star's shell begins to burn, once the shell of hydrogen has completely burnt the core helium begins to burn, then carbon burns, and so on burning through the elements [5]. As the layers of the shell burn off the density and temperature of the star increases. During the shell burning neutrinos are being produced and emitted. After the helium burning, the neutrino emission increases, also called "neutrino cooling". The neutrinos leaving the star's core take energy with them. Once all the elements have undergone fusion except iron the shell burning stops as iron cannot undergo nuclear fusion.

At this point the core of the star stops generating heat and the pressure drops allowing all the material external to rush in. The core of the star begins to collapse on itself from the gravitational pressure. As the core is collapsing, free protons are captured by electrons and become neutrons, this is called "neutronization" and increases the rate of collapse. Neutronization produces significant amounts of electron neutrinos which can escape the collapsing core at the beginning. This initial escape of neutrinos is soon stopped as the material that is rushing in becomes dense. Neutrino trapping allows inverse beta decay to take place, evening out the number of electrons and ending the energy flow outwards.

The collapse stops when the core reaches nuclear densities. The material falling in rebounds outwards causing a shockwave, this shockwave allows the trapped electron neutrinos to leave the star in a "neutrino breakout".

The neutrinos leave in a burst taking 99% of the supernova's explosion energy, the neutrino breakout happens a few hours before the outer layers of the star are affected by the shockwave and produce light. The time gap between the neutrino breakout and an optical radiation allows an advance warning so that the early stages of a supernova can be visually observed by astronomers. The neutrinos themselves can also provide information on what takes place in the core of a star when it collapses like the nuclear and sub-nuclear processes as well as information on how neutron stars and black holes are formed.

At this point the star can either become a neutron star or a black hole. This depends on the mass of the collapsed core. If the collapsed core is less than 3 $M_{\odot}$ the collapse may stop due to neutron pressure creating a neutron star. The stop due to pressure causes a shockwave heading outwards through the star's layers in a core-collapse supernova explosion[7]. If the mass of the collapsed core is greater than 3 $M_\odot$ gravity will cause the pressure to collapse into a blackhole.

If the collapsed proto-neutron star in the supernova is between 1.4 and 3 $M_\odot$ it becomes a neutron star. The critical mass for core-collapse is the iron core being 1.4 $M_\odot$. This happens because neutrons form from the electrons and protons [4]. Neutron stars are very dense and have a large gravitational force at the surface of the star.

Neutron stars then, under the right conditions can become pulsars. Pulsars were discovered in 1967 and appear to be flickering stars but are in fact neutron stars that are rotating emitting two beams in opposite directions. The flickering comes from the rotation of the pulsar, which causes magnetic fields. The stars that form pulsars spin and as the star collapses and more material goes to the centre during a supernovae the rotation speed of the, now collapsing, star will increase, this spin will continue even once the star has finished "dying" and becomes a neutron star [8]. Since pulsars are so small and so dense getting them to spin at the millisecond rate that some spin at requires an extra energy source, often taking energy and matter from a nearby star if they are in a binary system. This stolen energy and matter will increase the pulsars spin rate as well as eventually consume the nearby star. These pulsars that are drawing from a a star are often referred to as black widow stars.

The radiation from pulsars can be in any wavelength from radio waves up to gamma rays. The spinning magnetic field creates an electric field causing particles to move via electric current. This current can cause the different wavelengths that the pulsar produces [8].

If the core of the star in the collapsing supernova is more than 3 $M_\odot$ the star continues to collapse until it turns into a black hole. Black holes are infinitely dense and thus have extremely strong gravitational pull so that nothing can escape the black hole once it's been pulled in. Black holes can only be detected indirectly as astronomers use photons to detect objects in space and not even light can escape a black hole [4].

Eventually if there is dust and debris left from the supernovae it will merge with any gas and dust and the remnants from the old star will become part of a new star or planetary system.

2.2 Types of Supernovae

Astronomers have classified supernovae into two types as well as several subtypes. Type I supernovae have no hydrogen absorption lines in their spectrum [9] whereas Type II supernovae have clear hydrogen absorption lines [9]. The subtypes are Ia, Ib, Ic, II-L and II-P. Type Ia have been used by astronomers to estimate the size and shape of the universe. HALO-1kT is interested in types Ib, Ic, II-L, and II-P as they are all core-collapse supernovae. Core-collapse supernovae release more neutrinos, are easier to understand, and easier to detect. Type Ia supernovae are less frequent than core-collapse but produce significantly more iron and are brighter at peak. These supernovae have become known as "standard candles" to the astronomical community due to their bright light and the ability to measure the expansion of the universe using them.

HALO and HALO-1kT are particularly interested in core-collapse supernovae, which are all type II and type Ib and c. These supernova happen in stars greater than 8 $M_\odot$.

Chapter 3

The Physics of the Neutrino

Neutrino physics is a modern field of physics research, the idea of neutrinos only being proposed in 1930 by Wolfgang Pauli. At the time the technology to study neutrinos was not yet created. The first section of this chapter, the history of the neutrino, will detail early neutrino research, focusing primarily on Reines and Cowan's work in the 1950s and 1960s, as well as discuss experiments that Reines and Cowan's work paved the way for that took place from the 1970s through the 1990s. The second section of this chapter will discuss the standard model and how neutrinos fit into it and how they don't fit into it. The final section of this chapter will discuss modern neutrino detection, the various types of detectors that are currently being used around the world.

3.1 The History of the Neutrino

Pauli proposed neutrinos in 1930 as a way of explaining why the electron from beta decay had a continuous energy spectrum instead of the expected peak. A few years later in 1934 Enrico Fermi developed the mathematical theory that included a massless neutrino in beta decay [10]. At this time there was missing energy in the beta decay spectrum[11].

Around this time, James Chadwick was interested understanding the mass of atoms. The electron and proton were known and understood. The atomic nucleus was also observed, but the misalignment of the atomic number and mass number was not yet explained. There were various theories, one theory was that there were extra protons in the nucleus and an equal number of extra electrons to cancel the extra charge. Another theory was that the electron and neutron combined to make a new particle.

However in 1930 a few experiments were done that used alpha particles, from polonium, to bombard beryllium and to study the resulting radiation. It was assumed by some that the resulting radiation was high energy photons but some strange features lead Chadwick to think the radiation may be the predicted neutral particle. One of these experiments found that when the radiation hit paraffin wax protons from the hydrogen atoms recoiled with high velocity. The radiation must have mass to cause the protons to move, so in 1932 Chadwick tried similar experiments and determined the radiation was a neutral particle that had slightly more mass than a proton and the particle could penetrate further into a target than a proton. In 1932 he submitted a paper called "The Existence of a Neutron" and won the Nobel Prize in 1935 for the discovery. [12]

In the early 1950s a collaboration was formed called Project Poltergeist. The goal was to use the newly created atomic bombs to detect neutrinos. Fred Reines, a theorist on the Manhattan project, and Clyde L. Cowan were the initial members of the collaboration. They decided it would be best to detect the neutron and positron produced by an inverse beta decay reaction to find the neutrino, as it is impossible to detect a neutrino directly.

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{n} + e^+ \tag{3.1}$$

Inverse beta decay is when an antineutrino interacts with a proton and produces a neutron and a positron. Also in the early 1950s several groups discovered when a charged particle passed through certain liquid scintillator, the liquid scintillates releasing light.

In 1952 Reines and Cowan went to a conference where J.M.B Kellogg suggested using a fission reactor instead of an atomic bomb as a source. An atomic bomb provides a higher flux of neutrinos than a reactor, and at the time of this suggestion the available shielding would make background equivalent. Using a nuclear reactor as the source would allow the ability to have long term data collection of a consistent source. Reines and Cowan had an idea to use Compton scattering to detect both the positron and the neutron by adding cadmium to the liquid scintillator. The cadmium captures the neutron and releases energy in the form of 9 MeV gamma rays. This would allow for a delayed coincidence signal, which is two flashes of light within 3-10 microseconds with well defined energy ranges. By using a delayed coincidence signal to discriminate between backgrounds and inverse beta decay reactors became a viable source to detect neutrinos.

After a few design iterations they decided on having two water tanks sandwiched between three scintillator detectors. The water tanks with cadmium chloride dissolved into the water provided targets for protons and allowed for neutron capture.

$$n + {}^{108}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd}^{*} \rightarrow {}^{109}\mathrm{Cd} + \gamma \tag{3.2}$$

The scintillator tanks each were surrounded by 110 PMTs, allowing for the identification of the spatial origin of events as well as ensuring only delayed coincidence events were recorded. A delayed coincidence event being two events taking place in two of the three scintillator detectors that are detected that are not at the exact same time but within 3 to 10 microseconds of each other. The detector was placed in the basement of the reactor building, which provided enough shielding to reduce cosmic rays.

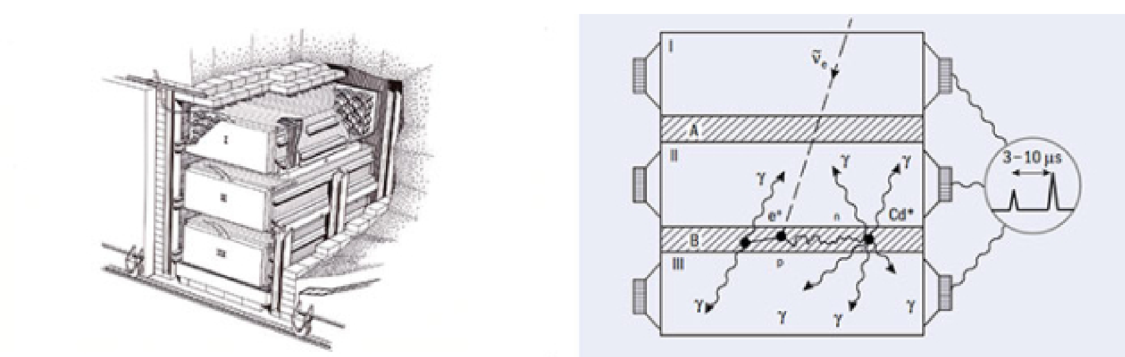

Figure 3.1: Savannah River experiment design [10].

Project Poltergeist collected 900 hours of data when the reactor was on and 250 hours of data when the reactor was off; there were five times more events when the reactor was on, which was one reactor event per hour. After double checking the results they were sure, they were within five percent of the theoretical value for the inverse beta decay cross section confirming the first ever detection of neutrinos.

In 1962 muon neutrinos were detected for the first time at Brookhaven National Lab. Using an accelerator's beam to produce a pi meson shower, these pi mesons traveled towards a steel wall made of 5,000 tons of old battleship plating. By the time the pi mesons got to the wall they had decayed into muons and neutrinos, the muons would be stopped but the neutrinos would pass through the wall and a tiny fraction could interact with a detector. The detector was a spark chamber that when the neutrinos interacted with aluminum plates trails of sparks created by produced muons could be detected and photographed [13]. This was the discovery experiment for muon neutrinos.

In 1964 an experiment was proposed, and performed in 1968 called the Homestake experiment [14], that would use 100,000 gallons of dry cleaning fluid to detect neutrinos from the sun. When the data was analyzed there were found to be approximately only a third of the expected number of neutrino interactions; this was the first indication of neutrinos changing flavours. Raymond Davis Jr, who headed Homestake, and Masatoshi Koshiba, who worked on Kamiokande and Super-Kamiokande, were awarded one half of the 2002 Nobel Prize in physics for the detection of cosmic neutrinos [15]. At this point it seemed as though all neutrinos were either electron neutrinos or muon neutrinos. A few years later in 1975 at the Stanford Linear Accelerator another lepton was discovered. The existence of the tau lepton implied there would also be a tau neutrino which is produced when the tau decays [13]. The tau neutrino was first detected in 1997 by direct observation of the nu tau, by the DONUT experiment, at Fermilab, announced their results in July 2000.

The Kamioka Nucleon Decay Experiment, KamiokaNDE, was built in 1982-1983 in Japan. Located in the Mozumi mine 1 km underground, it had 1000 PMTs attached to a tank that was 16 m tall and 15.6 m in diameter that was submerged in 3000 tons of pure water. This allowed KamiokaNDE to observe nucleon decay and neutrino events. Around the same time IMB experiment was being built as well. A 20 m cubical tank full of ultra-pure water having 2048 PMTs was built in the Morton salt mine, near Cleveland Ohio, 610 m underground. On February 23, 1987, KamiokaNDE detected 11 neutrinos from a supernova in the Large Megellanic Cloud. The IMB experiment detected 8 neutrinos from Supernova 1987A.

KamiokaNDE confirmed that the amount of neutrinos coming from the sun was less than expected. This in combination with the Sudbury Neutrino Observatory's, SNO, observations in the late 1990s and early 2000s on solar neutrinos confirmed that neutrinos can oscillate between types. SNO was a water Cherenkov detector built in Creighton mine in Sudbury, ON. It was an acrylic vessel 12 m in diameter filled with heavy water, D_2O inside a 20 m cavity filled with ultrapure water. SNO was surrounded by 9643 PMTs. [16] It used neutron capture to release gamma rays that Compton scattered electrons that, when met the Cherenkov threshold, as described in Section 3.3, would be detected by the PMTs. The results of Kamiokande and SNO showed that neutrinos could change flavours. [16] Since then several experiments have taken place to study neutrinos to learn more about how they fit into the standard model.

In 2015 Takaaki Kajita and Arther B. McDonald, heads of the KamiokaNDE and SNO experiments respectively, were awarded the Nobel Prize in Physics for discovering neutrino oscillations showing neutrinos have mass[17].

3.2 Neutrinos in the Standard Model

The standard model is a unified system for classifying elementary particles, there are main types of particles: Quarks, leptons, and bosons as seen in Figure 3.2. All particles are classified by their charge and spin. Quarks and leptons have three generations of particles as settled by the LEP experiments, commissioned in 1989 [19].

Leptons are fundamental point-like particles with no internal structure. They only interact by the electromagnetic and weak forces; neutrinos only interact by weak interactions as they are uncharged. Each lepton has a lepton number which is a set of quantum numbers that are individually conserved per generation. The lepton number being individually conserved means there is pair production, as experimentally observed, for example the electron and the positron.

Quarks are believed to be point-like particles, there are hints that they have a substructure but there is no evidence yet to prove that there is a substructure. Quarks interact by strong, electromagnetic, and weak forces. Quarks have a charges of +/- 2/3 e or +/- 1/3 e. Quarks, unlike leptons, must bind together. There are always 2 or 3 together.

In the standard model neutrinos don't have mass. This would mean it is impossible for neutrinos to mix and change flavours, but, as previously discussed, this was disproven by KamiokaNDE and SNO. The following section will discuss the main types of neutrino detection used for supernova neutrinos.

3.3 Neutrino Detection

Neutrinos are detected through weak interactions only. Either by neutral current(NC) Z° exchange or through charged current(CC) $W^{+/-}$ exchange.

There are a few main types of neutrino detectors based on their target material: water Cherenkov, liquid scintillator, and lead. All three types of detectors have their benefits, drawbacks, and different neutrino type sensitivities. At supernova energies, water Cherenkov and liquid scintillator detectors are sensitive to electron anti-neutrinos via inverse beta decay interactions on protons. Lead detectors have no electron anti-neutrino sensitivity through CC interactions but have electron neutrino sensitivity through CC interactions and is sensitive to all neutrino flavours through NC interactions.

Water Cherenkov detectors use water as the target for neutrinos. In the case of the original SNO experiment, it was heavy water but in the case of IceCube it is ice as a target. Other experiments have used pure or ultra-pure water. The "Cherenkov" comes from Cherenkov radiation, when a charged particle moves through a substance faster than the speed of light in the same substance it produces Cherenkov radiation causing light that can be detected by photomultiplier tubes. Muons and electrons can be separated using ring morphology, which is how the light pattern appears on the photomultiplier tubes [20].

One of the benefits of water Cherenkov detectors is that you can get a large mass, and thus a large target for neutrinos, for a relatively low cost. Water Cherenkov detectors also have a threshold determined by the background level. The lower the background levels the lower the threshold.

Liquid scintillator detectors use a scintillator as the target. A scintillator is often a transparent organic liquid, like mineral oil, made specifically for the experiment. When a charged particle passes through a scintillator it produces a flash of light, this process is called scintillation. This light can be detected using photomultiplier tubes, PMTs [20].

The scintillation process produces more light than Cherenkov radiation, due to the lower threshold for scintillation. Liquid scintillator can therefore be used to detect low energy particles, allowing for a different energy range to be seen and studied in comparison to water Cherenkov detectors. One of the downsides of using a scintillator is it is more expensive to buy and purify than water.

Lead detectors use lead as the target for neutrinos. A neutrino can interact with the lead through a CC reaction producing a neutron.

$$\nu_{\mathrm{e}} + Pb \rightarrow \mathrm{e}^{-} + Bi^{*} \tag{3.3}$$

$$Bi^{*} \rightarrow Bi + \gamma + \mathrm{n} \tag{3.4}$$

Through the NC reaction lead-based detectors are sensitive to all three neutrino flavours, unlike other supernova detectors.

$$\nu_{\ell} + Pb \rightarrow {\nu_{\ell}}' + Pb^{*} \rightarrow Pb + \gamma + \mathrm{n} \tag{3.5}$$

Where ν_{ℓ} is any flavour of neutrino.

Detectors that use lead as a target do not have to worry about leaks or purifying a liquid or having tanks to store liquid before it goes in the detector. Lead is also sensitive to all types of neutrinos which other types of neutrino detectors are not, and generally only sensitive to one or two types on neutrino. Lead has a high neutrino interaction cross section and a low neutron capture cross section, meaning neutrinos are likely to interact and produce a neutron but that neutron is less likely to be captured on the lead and will be available to be captured in the counters the experiment uses[20]. The neutron excess in lead Pauli-blocks the electron anti-neutrino CC interaction making a lead-based supernova detector complimentary to water Cherenkov and liquid scintillator supernova detectors.

As seen in this chapter, there are many ways of detecting neutrinos, the next chapter will go further into why lead was chosen and how HALO-1kT will work and the original HALO detector.

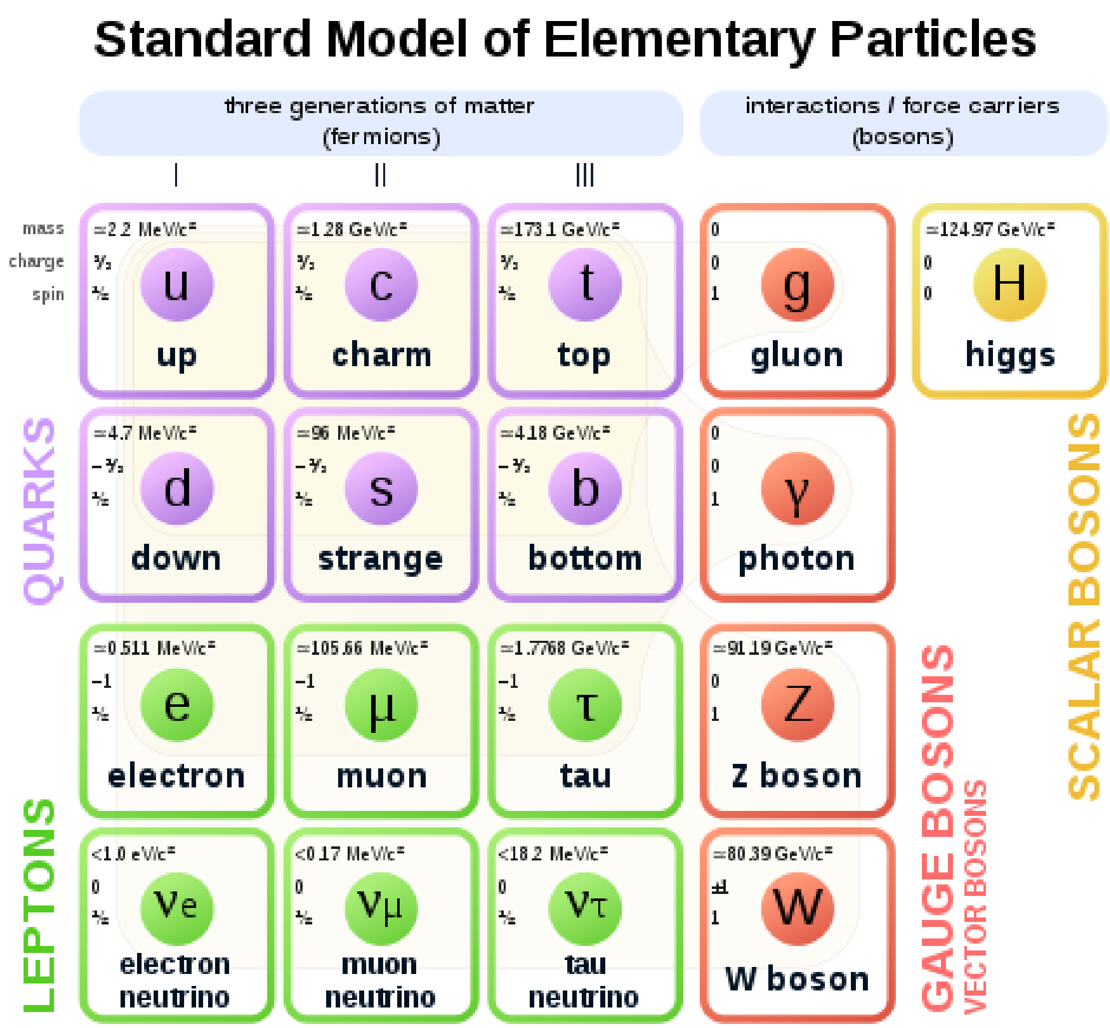

Figure 3.2: The Standard Model [18].

Chapter 4

HALO-1kT

In the previous chapter various types of detectors were discussed. This chapter will go deeper into choosing lead as the target and using He-3 counters as well as why lead and He-3 pair well together. This chapter will also give an explanation of HALO-1kT's operating prototype detector HALO and finally detail the plans for HALO-1kT.

4.1 Lead as a Target

Lead is an excellent target for supernova neutrinos as it is sensitive to every flavour of neutrino with a primary sensitivity to electron neutrinos [21]. Its sensitivity to neutrinos was shown in Equation 3.5. Lead has the largest charged and neutral current cross section of any reasonable material. The higher Atomic number, Z, the higher the electron neutrino charged current cross section compared to the electron anti-neutrino charged and neutral current cross sections. This is due to Coulomb enhancement of the electron neutrino charged current channel and a Coulomb suppression of the electron anti-neutrino charged current channel. There is a de-excitation by 1n or 2n emission following a charged or neutral current interaction. The neutron excess, N larger than Z, in lead produces Paul-blocking of the electron anti-neutrino CC channel which would convert protons into neutrons in the nucleus. The charged current interactions are: $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n}$

$+e^-$ and ν_e + ^{208}Pb $\rightarrow^{206}$Bi + 2n + e^-. Their kinematic threshold energies are 10.2 MeV and 18.1 MeV, respectively, this is weighted over the isotopic abundances. The neutral current interactions: ν_e + ^{208}Pb $\rightarrow^{207}$Pb + n and ν_e + ^{208}Pb $\rightarrow^{206}$Pb + 2n have weighted threshold energies 7.4 MeV and 14.4 MeV respectively[20] .

Lead has a high neutrino interaction cross section and is primarily electron neutrino sensitive which is complementary to the water Cherenkov and liquid scintillator detectors. Lead detectors are lower maintenance and have a longer lifetime than water or scintillator detectors allowing for decades long experiments with very little downtime. Lead-based detectors also don't need to worry about containing liquids or leaks compared to their liquid-based counterparts.

The lead in an experiment could contribute to the experimental backgrounds. Recently, ancient underwater lead has become popular for use in particle physics. This is because lead that has been underwater since before the first atomic bomb test in 1945 has not been contaminated by the radioactivity that has been put into the atmosphere since 1945 [22]. HALO's lead was from a decommissioned cosmic ray experiment, Deep River Cosmic Ray Station [23]. The lead HALO-1kT is going to use is not ancient underwater lead but does have known backgrounds and would come from the Oscillation Project with Emulsion-tRacking Apparatus, OPERA [24].

As an emulsion detector, OPERA aimed to have low backgrounds in its lead. After searching and testing lead samples they found three companies that met that requirement. The limit estimates 1 fake track/mm^2. This low radioactivity lead came from Boliden mine in Sweden [25].

4.2 Helium-3

He-3 is the other main component of the HALO detectors. He-3 is a controlled substance, produced by the decay of tritium. In America, where the HALO-1kT counters would be produced, it is solely produced and controlled by the US Department of Energy, DOE.

The DOE exclusive source of He-3 comes from the biproduct of radioactive tritium decay as part of the tritium processing that the National Nuclear Security Administration does at the Savannah River Site in Southern Carolina. Certain crucial applications have access to thousands of litres of He-3 gas annually [26]. There was a moratorium on He-3 use post 9/11 due to an anticipated increase in demand for its use in counter-terrorism, however the memorandum has since been lifted. Mitigation efforts have been put into place to ration usage of He-3 so demand doesn't exceed supply [26]. There are only two companies who are able to use the DOE's supply of He-3 for proportional counters.

He-3 has 2 protons and one neutron. He-3 has a high neutron absorption cross section making it pair well with the lead which produces neutrons when interacting with neutrinos. The neutron produced from the lead neutrino interaction slows down and is captured in the He-3 counters producing a proton, a triton, ^{3}H, and 764 keV. However, if the neutron capture on He-3 is close to the wall of the counter it is possible that the proton or the triton can hit the wall and not deposit all of its energy into the gas. This means that there are two bumps in the energy spectrum as seen in Figure 4.1 at 191 keV, the proton escape peak, and 573 keV, the triton escape peak. There is also a low energy background that can overlap with the lower energy parts of the neutron window.

$$^{3}\mathrm{He} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + \mathrm{p} + 764\,\mathrm{keV} \tag{4.1}$$

Both the produced triton and proton ionize the gas, the ionization tracks drift and land on the anode wire. The energy from the ionization tracks are then sent to a DAQ system, in HALO's case two DAQs are used and alternated for redundancy and to ensure no supernova is missed. With perfect energy resolution the neutron window, where the energy corresponds to neutrons, is from 191 to 764 keV. With HALO's energy resolution it is from 150 to 850 keV. However, due to overlap with the beta - gamma low energy tail, and because HALO was essentially background free above 850 keV, HALO used a neutron window of 250 to 1000 keV.

4.3 HALO: a Prototype of Opportunity

The Helium And Lead Observatory at SNOLAB in Sudbury, Ontario is a running prototype for HALO-1kT. HALO was a detector of opportunity: SNO used He-3 proportional neutron counters and when SNO was being repurposed into SNO+, there was no longer a use for these counters.

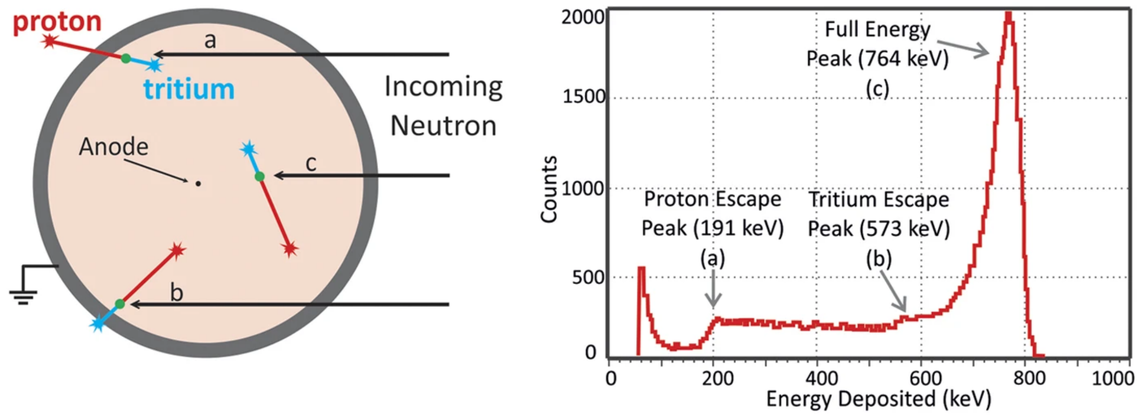

Figure 4.1: The right figure shows a proportional counter and how depending on where the neutron He-3 interaction takes place it is possible to have the proton or triton hit the wall. The left figure shows the plot of the energy deposited with two bumps at 191 keV for the proton escape peak and at 573 keV for the triton escape peak. It also shows the full neutron peak at 764 keV and a low energy gamma tail [27]. In this figure (a) shows where the proton escapes and the energy of just the tritium getting deposited, (b) shows where the tritium escapes and only the proton energy is deposited, and (c) shows the full energy peak where both the proton and the triton deposit all their energy into the gas.

During SNO these were called neutral current detectors, NCDs, for HALO neutron detectors are a more appropriate name. A group of scientists came up with the idea to repurpose them into a supernova detector using lead from the Deep River Cosmic Ray Station and He-3, this group became the HALO collaboration. 128 of these He-3 proportional counters were used in HALO. They are 5 cm in diameter and 2.5 to 3 m long. The counter body is ultra-pure CVD nickel with a 600 micron wall thickness. They are surrounded by 79 tonnes of lead. HALO is often referred to as a detector of opportunity due to being able to use the NCDs from SNO and the lead from the Deep River Cosmic Ray Station.

Figure 4.2 shows HALO before the final wall of ultra-pure water shielding was in place. Inside the shielding is the structure that holds the lead and counters. The lead is painted green, in each column of lead are four counters inside high-density polyethylene moderator tubes. There are a total of 32 columns of lead, the counters in each column are paired, for detector read-out proposes resulting in 64 channels of electronics.

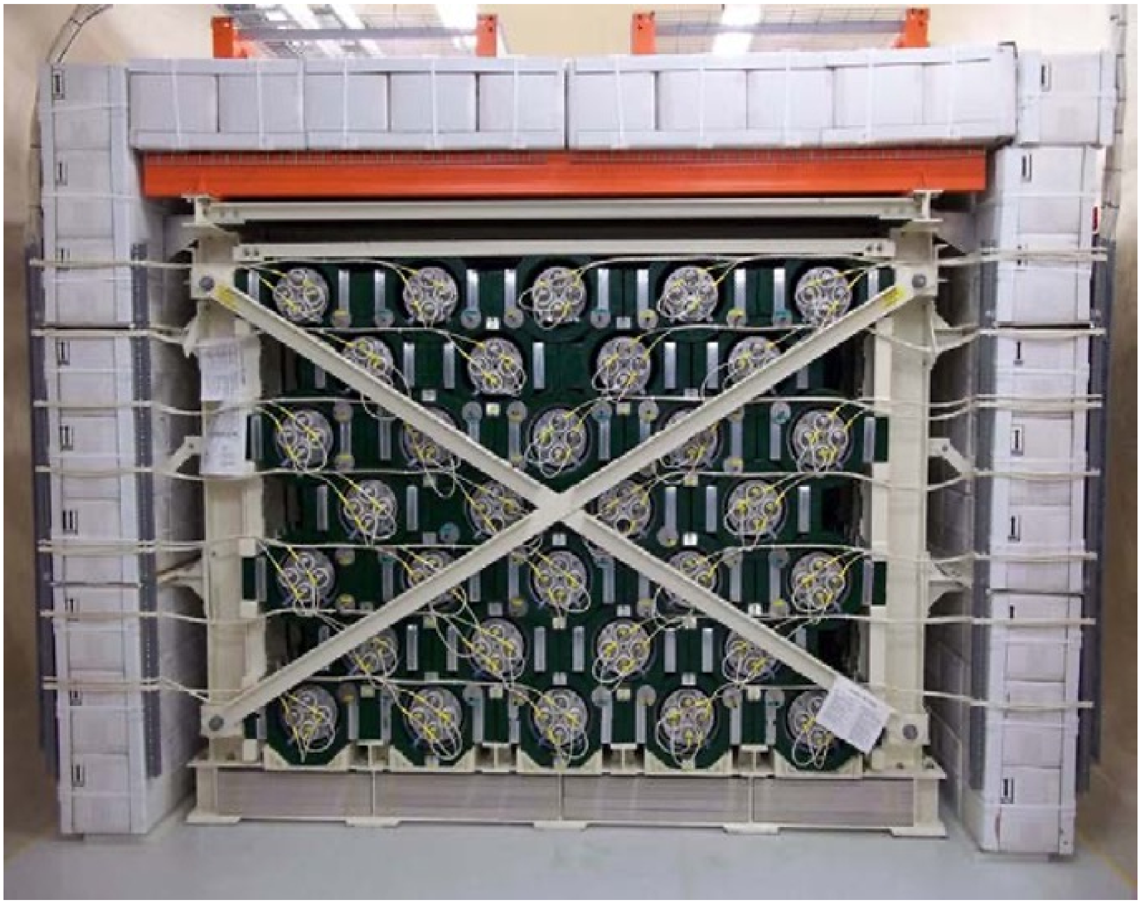

Figure 4.2: HALO at SNOLAB

The science goal of HALO is to detect a supernova. An added benefit of HALO is that it is a low cost, low maintenance, long lifetime supernova detector. As most other neutrino detectors have other, non-supernova-related science goals, they also require downtime and calibration time making it more possible to miss a supernova. Another factor considered was that as costs go up with the next generation of neutrino detectors the energy threshold of those detectors may go up, decreasing supernova sensitivity.

HALO has a SNEWS trigger of 4 events in the neutron energy window within a time window 2 seconds. At the measured HALO neutron rate of 15 mHz random coincidences are expected once every two years. Spallation events are suppressed and include any series of events that are over in less than 1ms, these events do not generate a SNEWS trigger nor are they limited by background rates. HALO is sensitive to supernovae out to 18 kpc which is limited by target mass. HALO has a lifetime uptime of 99% , with the full detector being read out since May 8, 2012 with daily shifts since July 27, 2012. HALO has been connected to SNEWS with burst implementation since October 8, 2015.

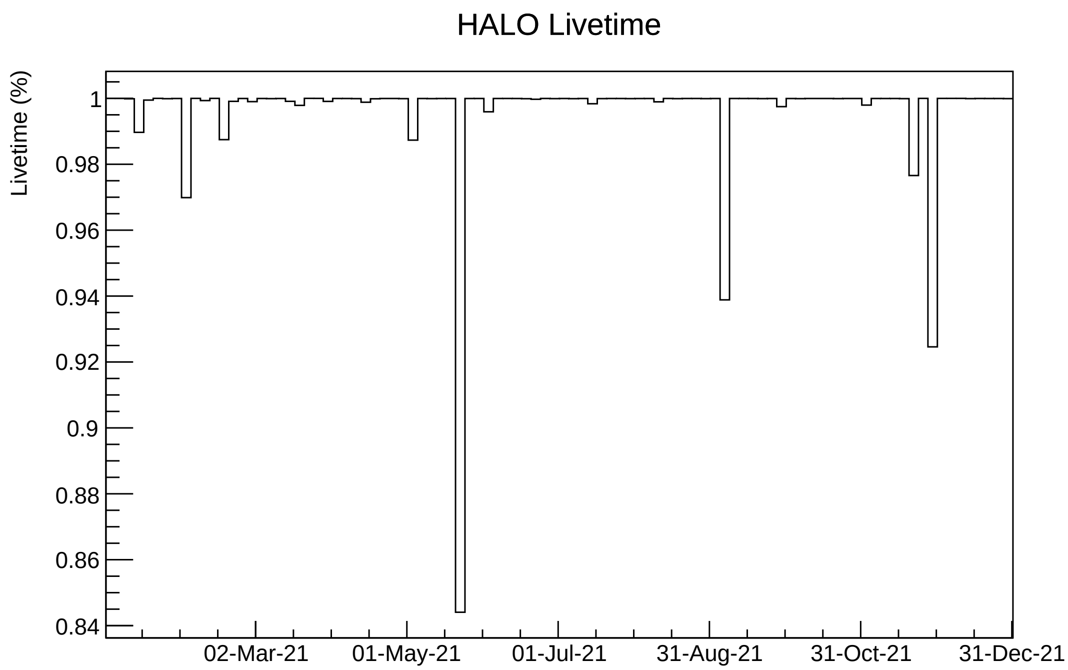

Figure 4.3: HALO live time in 2021. Time bins represent a week of data taking. The vertical axis has a suppressed zero.

HALO was able to stay operational throughout the 2020 pandemic lockdowns with an overall live time in 2020 of 99.19% . This is interesting as many experiments had to go into “care and maintenance” mode through the early stages of the COVID-19 pandemic while access to the detectors was limited, but HALO continued to take data throughout stay-at-home orders and restricted underground access at SNOLAB. Had a supernova happened during this time HALO would have

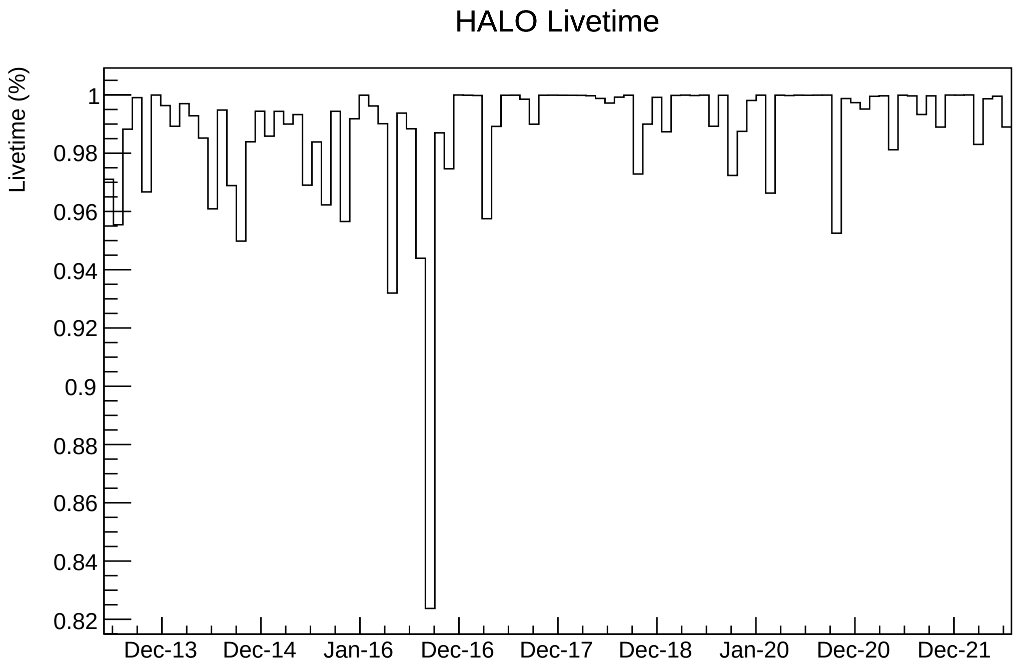

Figure 4.4: HALO live time for its entire operating period from 2013 to 2022. The vertical axis has a suppressed zero.

been live and collecting science data. The 2021 live time graph can be seen in Figure 4.3. A lifetime live time graph can be seen in Figure 4.4. HALO-1kT has an aim to operate with the same amount of live time.

4.4 HALO-1kT Details

HALO-1kT is the next generation of lead-based supernova detector on both a larger scale and with a larger collaboration adding members from both Italy and America. The HALO-1kT collaboration formed due to the availability of 1 kT of lead from the now disassembled Oscillation Project with Emulsion-tRacking Apparatus, OPERA. OPERA was a tau and muon neutrino oscillation detector in the LNGS in collaboration with CERN that ended data collection on December 3, 2012. LNGS has gamma background of 0.3 cm^{-2} s^{-1} [28].

The 1 kT of lead combined with approximately 4.3 km of proportional counters will allow for a much greater sensitivity than the original HALO experiment's 79 T of lead. By increasing the amount of lead to 1 kT, the neutron capture efficiency will go from 28% for HALO to approximately 53% for HALO-1kT giving 23 times the event statistics. Relative to HALO, HALO-1kT expects to see hundreds of events for a supernova at 10 kpc. In order to achieve this goal HALO-1kT has a target total background budget of 0.5 Hz from all sources, with the 4.3 km of neutron counters themselves having an internal target budget of 0.25 Hz. The 0.5 Hz was determined by Dr. Andrea Gallo Rosso, it was chosen as it would provide an acceptable rate of false SNEWS triggers while still being able to see a supernova across the entire galaxy [29]. With 0.5 Hz from all background sources in HALO-1kT it was determined that each individual source could account for at most 1/10th of that, allowing 0.05 Hz per individual source.

HALO-1kT, as seen in Figure 4.5, is much larger than the original HALO prototype at SNOLAB. The lead and proportional counters are surrounded by 30 cm of graphite reflector and 30 cm of high-density polyethylene shielding. The proportional counters are arranged in a 28 x 28 x 5.5 m array inside the lead.

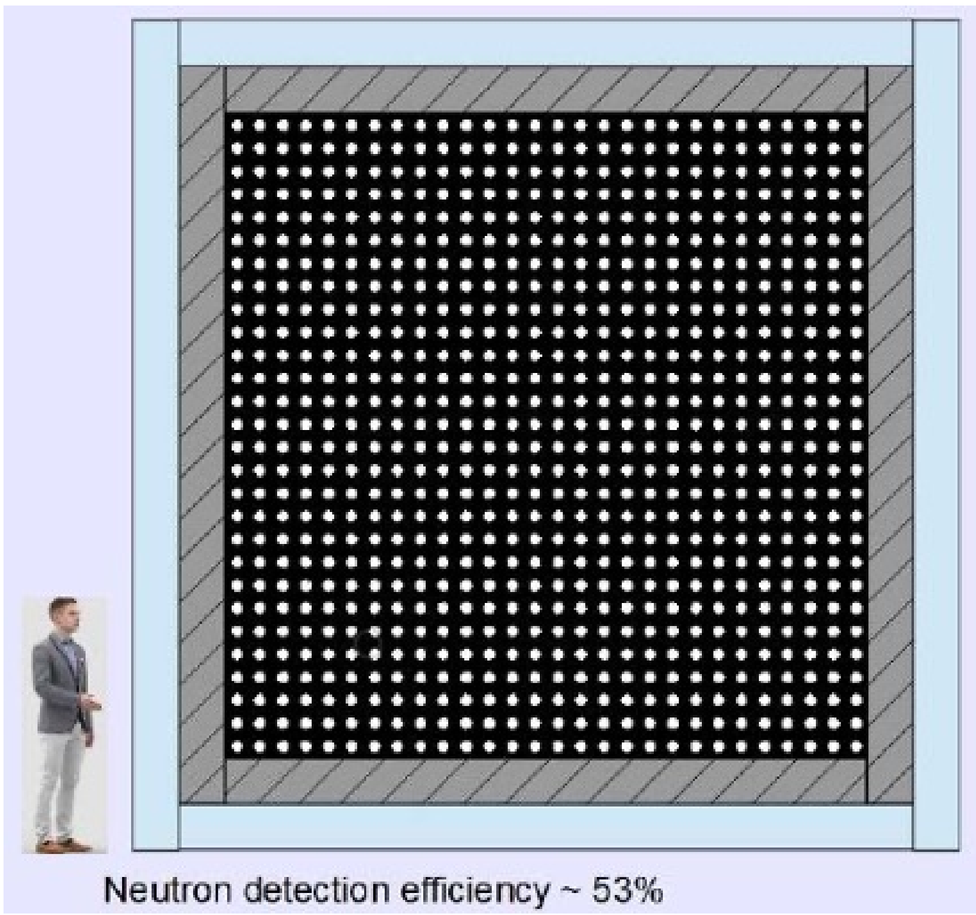

Figure 4.5: HALO-1kT preliminary drawing

Chapter 5

The Supernova Early Warning System

The Supernova Early Warning System, or SNEWS, is a global collaboration of primarily neutrino experimentalists and astronomers. The goal is that when a supernova happens next the neutrino experiments will detect the neutrino burst and be able to provide astronomers an with early warning so they can point their telescopes and get a visual of a supernova early in its explosion as well as information on what happens inside a supernova as it explodes.

5.1 A World-Wide Collaboration

SNEWS and SNEWS 2.0 are world-wide collaborations with experiments in Antartica, Asia, Europe, and North America, as seen in Figure 5.1

5.1.1 Current Global Experiments

SNEWS has seven active neutrino experiments as well as various decommissioned experiments [31]. SNEWS 2.0, which is currently in development, will have many more experiments that are

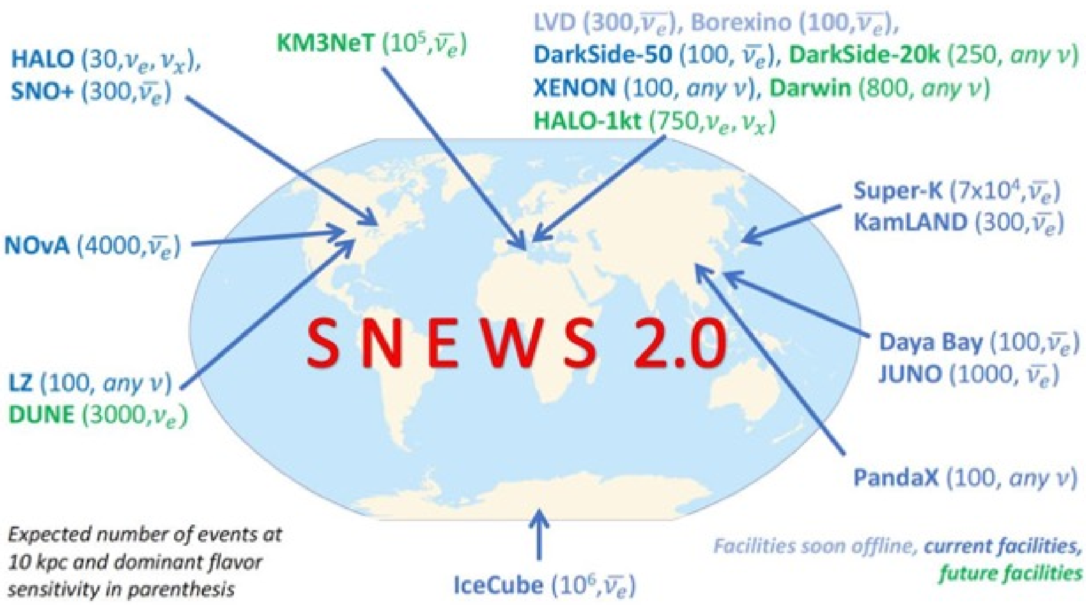

Figure 5.1: The map of SNEWS 2.0 from the 2018 NSF proposal, the expect number of events for some experiments have changed since this was created due to a better understanding of their cross sections [30].

comprised of several different types of detectors that are sensitive to galactic supernova neutrinos, including but not limited to water Cherenkov, liquid scintillator, lead-based, and liquid noble dark matter detectors [32]. Several of these experiments are discussed here as well as experiments that are planned but not yet operational. Table 5.1 summarizes these experiments, the type of the detector they are, their mass, location, live period from construction competition, as well as how many events they expect to detect from a supernova at 10 kpc.

Super-Kamiokande

Super-Kamiokande [33] is an experiment in Mt. Ikeno, Japan with an overburden of 2700 meter water equivalent (m.w.e.) that began taking data in April 1996. It is a water Cherenkov detector that uses 50 kT of pure water in a stainless steel tank that is 32 m in diameter and 42 m tall [33]. The tank is then split into two detectors, an inner and outer detector. The inner detector

Table 5.1: Summary of SNEWS 2.0 detectors with supernova sensitivity

Detector	Type	Mass (kT)	Location	Events expected for a Supernova at 10 kpc	Live period
HALO	Lead	.79	Canada	30	2012 - present
Super-Kamiokande	Water Cherenkov	22.5	Japan	4000 - 8000	1996 - present
LVD	Liquid Scintillator	1	Italy	300	2001 - present
IceCube	Long String Cherenkov	0.6/PMT	South Pole	N/A	2011 - present
KamLand	Liquid Scintillator	1	Japan	100 - 300	2002 - present
Borrexino	Liquid Scintillator	0.28	Italy	100	2007 - 2021
KM3Net	Long String Cherenkov	N/A	Europe	50 - 250	Future
Baksan	Liquid Scintillator	0.33	Russia	50	1980 - present
Sno+	Liquid Scintillator	0.78	Canada	300	2020 - present
NOvA	Liquid Scintillator	14.3	USA	4000	Near Future
HyperK	Water Cherenkov	260	Japan	110,000	2027
JUNO	Liquid Scintillator	20	China	2000	2023
DUNE	Argon	0.7	Italy	340	Future
Darkside-20k	Argon	0.2	Italy	340	Future
XENON1T	Xenon	.2	Italy	350	Future
HALO-1kT	Lead	1	Italy	Hundreds	Future

has 11,146 PMTs that are 50 cm in diameter and face inwards, the outer detector has 1,885 PMTs that are 20 cm in diameter that face outwards. SNEWS only uses the events in the inner detector, which is 32 kT of active mass. Supernova neutrinos are mainly detected through inverse beta decay. There is an expected 4,000 - 8,000 events for a Supernova that happens 10 kpc away. Although Super-Kamiokande also will have some supernova neutrinos that interact by elastic scattering on electrons (120 - 250 events), and a few neutrinos that have interactions on oxygen (80 - 250 events) [20].

The SNEWS signal for Super-Kamiokande is taken from the inner detector less 2 m at the walls giving a fiducial mass of 22.5 kT with energy visible greater than 7 MeV. The signal to SNEWS is based on selected events in that volume in 20 seconds. If there are more then 60 events in a volume-like distribution a “golden” warning is generated, this golden warning doesn’t need any other experiments to confirm for a global announcement to be sent. If there are 25 events to 59 events and a volume-like distribution a “normal” warning is sent to Super-Kamiokande experts and to SNEWS for combination and comparison with other experiments. Super-Kamiokande is also able to give a direction to the supernova with 3-5 degree angular resolution [20].

Large Volume Detector, LVD

The Large Volume Detector [34], otherwise known as LVD, is located in the INFN Gran Sasso National Laboratory, Italy and has an overburden of 3000 m.w.e. LVD is a modular 1 kT liquid scintillator detector made of an array of 840 counters that has been operational since 1992. Its main science goal is to study CCSN neutrinos through IBD interactions. The active mass was increased from 300 T to 1000 T at time of completion in 2001. After 30 years of continuous operations the experiment was planned to start its decommissioning phase at the end of 2020. It has been monitoring the entire galaxy and if a supernova happened at 10 kpc there are an expected 300 events. LVD was a founding member of SNEWS, and has been online since 2005 along [20] with Super-Kamiokande and SNO.

IceCube

IceCube Neutrino Observatory [35] is an experiment in Antartica in 1 km^3 the clear ice that uses Cherenkov light to detect inverse beta decays. IceCube finished construction in 2011 and was connected to SNEWS in 2015 with an average yearly live time of 99.7%. The experiment consists of an array of 5160 digital optical modules, DOMs. The DOMs are attached to 86 strings with 60 DOMs per string that are between 1450 m and 2450 m below the surface. Each DOM is spaced 17 m apart on the strings and has its nearest neighbour 125 m away horizontally on average [20]. IceCube is currently being upgraded with two new strings of multi-anode DOMs. IceCube can reconstruct arrival directions and energies of cosmic muon neutrinos. It is specifically optimized for neutrinos with energies between 10 GeV and 10 PeV and not able to reconstruct tracks from CCSN. However, it will expect 10^5 to 10^6 photoelectrons from a supernova at 10 kpc [20]. IceCube is sensitive to supernovae in the Milky Way and Magellanic clouds. If a statistically significant increase is observed an alert is sent to SNEWS with a latency of 5 minutes.

KamLAND

The Kamioka Liquid Scintillator Anti-Neutrino Detector [36], KamLAND, is a Scintillator detector in the Kamioka mine in Japan with an overburden of 2700 m.w.e. The detector is a 13 m diameter ballon filled with 1000 T of ultra pure liquid scintillator. The ballon is surrounded by a 18 m spherical stainless steel PMT array tank that has 1325 specially designed 17" PMTs and 554 inherited 20" PMTs. There is 3000 m^3 of pure water outside the tank that is a water Cherenkov detector for veto that has 140 PMTs. Since KamLAND is in Japan, its main source of backgrounds are the nuclear reactors, with a low energy IBD background of 0.1 events per day.

KamLAND expects 100 - 300 events for a supernova at 10 kpc and will send a SNEWS alert if there are 2 IBD events within 10 seconds. Pre-supernova neutrinos, which have a lower flux and lower energy put present for hours to days, can be detected although there is a 25 minute processing delay between detection and next actions. If the pre-supernova neutrinos have a significance greater than 3 sigma a collaboration meeting is called, depending on the results of that meeting a message may be sent to "The Astronomer's telegram"[20]. They are working on connecting to the Gamma-ray coordinates network and SNEWS 2.0. KamLAND is also planning on upgrading to new electronics and a new DAQ system to improve latency of supernova alarms and better measure low threshold proton recoils as well as to change the trigger threshold after 10 events.

The next generation of KamLAND will be a neutrinoless double beta decay experiment called KamLAND-Zen using Xe-136-loaded liquid scintillator which will conflict with supernova detection[20].

Borexino

Borexino [37] is an experiment at LNGS in Italy, which as previously mentioned, has 3800 m.w.e overburden. Its main science goal is to study solar neutrinos through elastic scattering on electrons and via inverse beta decay. It has a target mass of 278 T, which means there are limited expected event numbers from nearby supernova however it does have very low backgrounds due to the decreased muon flux of being under a mountain and there being no nuclear plants in Italy[20]. Borexino also has a low geo-anti-neutrino background, multilayer shielding, and made sure all materials were ultra-radiopure. The experiment joined SNEWS in 2009 and expects energies up to

50 MeV from a Supernova. Borexino is approaching its end and was planned to stop data taking in 2021.

KM3Net

KM3Net [38] is a collaboration between two deep sea neutrino detectors currently under construction in the Mediterranean sea. ORCA, whose main goal is neutrino oscillation studies, is being built offshore of southern France, and ARCA, whose main goal is neutrino astronomy is being built offshore Sicily. They use a similar design to IceCube in that multi-PMT DOMs are attached to vertical lines using the water of the sea as a Cherenkov detector. Each line, or detection unit, has 18 DOMs at depths from 2500 to 3400 meters arranged in a three dimensional array with over 6 000 DOMs and 200 000 PMTs. KM3Net has an effective mass of 40-70 kT [20]. The energy scale for CCSN neutrino sensitivity is of the order of 10s of MeV using inverse beta decay. A coincidence in at least six PMTs is used to make a selection for best sensitivity. With a background rate of 1 Hz per detection unit a supernova at 10 kpc KM3et would expect between 50 and 250 events in 115-lines. KM3Net is sensitive to CCSN beyond the galactic centre or in other words, depending on model considered, between 13 and 26 kpc for SNEWS with between 20 000 and 50 000 events [20]. The SNEWS alert goes out within 20 seconds of a supernova coincidence.

Baksan

One of the few experiments to observe neutrinos from SN 1987A the Baksan Underground Scintillation telescope [39] has been constantly watching for supernovae since 1980. In the Baksan Valley in Russia it has an overburden of 850 m.w.e.. It is a 330 T scintillator detector that detects IBD produced positrons. There are two sub-detectors with one having 130 T and an 8 MeV threshold with a background of 0.02 Hz, and a second one has 1120 T with a threshold of 10 MeV with a background of 0.12 Hz. Baskan has had an overall uptime of over 90% and would observe supernova events in both sub-detectors as well as another 90 T of scintillator [20]. There are plans to build a larger 10 kT detector with an overburden of 4800 m.w.e.

SNO+

SNO+ [40] is a detector at SNOLAB in Sudbury 2092 m underground with an overburden of 5980 m.w.e.. It is a scintillator detector that reuses and repurposes the original SNO detector and hardware, which is a 12 m acrylic vessel with 9300 PMTs in a geodesic support structure. Being so far underground allows for a very low background of cosmic muon flux of 63 muons/day in an 8.3 m radius circular area. The main goal of SNO+ is to observe the neutrinoless double beta decay of ^{130}Te using tellurium dissolved in linear alkylbenzene, LAB, and 2.5-diphenyloxazole, PPO. SNO+ started taking data in 2017 with water, in 2020 the acrylic vessel was filled with 780 T of scintillator and will load with tellurium of 0.5% by mass making for 1330 kg of the target isotope [20].

NOvA

NOvA [41] is two segmented liquid scintillator detectors that are almost identical but with different masses and in different locations. NOvA detects to neutrino interactions from the Fermilab NuMI beam. The two detectors are identified as the near detector and the far detector. The near detector is a 300 T detector 100 m underground at Fermilab near Chicago. The far detector is a 14 kT detector on the Earth's surface at Ash River in Minnesota, and though it is on the surface it has a small barite overburden. The detectors are made from extruded PVC cells that are 3.9 cm x 6.6 cm [20]. The PVC cells are filled with mineral oil and pseudocumene and are connected to form planes. The planes are then glued together to form a three dimensional full body detector by alternating between vertical and horizontal orientations. The photons produced bounce off the cell walls which are highly reflective until wavelength shifting fibres absorb them. The fibres are looped though through the cell. NOvA is sensitive to 8 - 15 MeV of detection energy with the most common interactions being inverse beta decay, followed by elastic scattering on electrons and NC interactions on carbon nuclei. The far detector has a cosmic muon rate of approximately 148 kHz. It is easy to identify and veto muons with software however more difficult to identify spallation products. When a supernova trigger happens 45 seconds of continuous data is recorded. The trigger is issued when signal significance exceeds a 5.6 sigma threshold which leads to a false alarm rate of once per week [20].

5.1.2 Future Experiments

Hyper-Kamiokande

8 km south of Super-Kamiokande under Mt. Nijuugo in Japan, Hyper-Kamiokande [42] is being built with an overburden of 1750 m.w.e. The experiment has a 260 kT mass, 40000 inward facing PMTs and 6700 outward facing PMTs. The design is effectively the same as Super-Kamiokande but on a larger scale which will result in better resolution and detection efficiency. It is expected to detect supernova up to 100 kpc away and is to start data taking in 2027[20].

JUNO

Jiangmen Underground Neutrino Observatory [43] is currently under construction 700 m underground in Jiangmen City, China, expecting to start data collection in 2022. It will be a multi-purpose neutrino experiment who's main goal is to determine the Neutrino mass ordering using reactor antineutrinos with an overburden of 1800 m.w.e.. The experiment has a central 20 kT liquid scintillator detector surrounded by a water Cherenkov detector which is surrounded by a muon tracker. The goal is to reach an energy threshold of 0.2 MeV with a dark noise rate of 50 kHz. JUNO will be able to observe all flavours of supernova neutrinos expecting 5000 inverse beta decay events for a supernova at 10 kpc, 2000 neutrino-proton elastic scattering events, and 200 neutrino-electron elastic scattering, plus CC and NC interactions. JUNO should be able to point w/ an uncertainty of 10 degrees [20]. JUNO will be able to provide pre-supernova and supernova alerts to SNEWS soon.

DUNE

The Deep Underground Neutrino Experiment [44], DUNE, will be a Liquid Argon Time Projection Chamber, LArTPC, that will be finished after 2026. LArTPCs detect electron neutrinos through their interaction on ^{40}Ar, which will complement the anti-electron neutrino sensitivity of many other experiments. The electron produced in the interaction of an electron neutrino on argon is detected by its drift track's charge. One of DUNE's main science goals is to detect CCSN in the

Milky Way, with an expected 3000 electron neutrino events for a CCSN 10 kpc away as well as the ability to point to the supernova [20].

5.1.3 Dark Matter Experiments

Most dark matter experiments are looking for weakly interacting massive particles, WIMPs. One way of detecting WIMPs is using noble liquids and these detectors can also be used to detect supernova. The liquid noble atom will scatter the WIMP or supernova neutrino causing scintillation light, phonons, and ionization electrons; the electrons and scintillation light can be detected. The liquid noble detectors have flavour insensitive neutrino detection.

Global Argon Dark Matter Collaboration

The Global Argon Dark Matter Collaboration, GADMC, is a dark matter collaboration using liquid argon to detect WIMPs. Current detectors, DarkSide-50 [45] and DEAP-3600 [46], have set limits for WIMP-nucleon interactions. Future detectors will be on the tonne scale with planed DarkSide-20k and Argo. DarkSide-20k is expected to be able to see 340 neutrinos from a supernova at 10 kpc and able to detect a CCSN up to 40 kpc[20].

Xenon

Using liquid xenon to detect WIMPs is the plan for the LZ and XENON collaborations. XENON1T is directly connected to SNEWS and is set up to save data when it receives alarms. The next generation of experiments for these two collaborations also wants to detect neutrinoless double beta decay as well as to be able to detect signals from CCSN anywhere in the Milky Way. At 10 kpc they would record 350 neutrino events. Both experiments are planning to have SNEWS integration and supernova trigger capabilities. The DARWIN collaboration wants to increase CCSN sensitivity with its next generation as well as possibly for closer supernovae be able to distinguish different models [20].

5.2 Alerting the Astronomers

There are specific conditions that need to be met before the astronomers get alerted. All experiments that are part of SNEWS send neutrino burst candidates to a central computer at Brookhaven National Lab. If there is a coincidence within 10 seconds an automated alarm message goes to astronomers [31]. The original astronomer working group determined at the 1998 SNEWS workshop that as long as an email was sent to as many astronomers as possible the news would spread quickly and SNEWS wouldn't need to do anything else. The alert should provide an event time and sky error box where astronomers could point their telescopes. The error box depends on which experiments are online and where the supernova is located. This alert is also to give astronomers time to prepare to gather data. Both professional astronomers as well as amateur astronomers are part of the group on the lookout for alerts and to help pinpoint the exact location of a potential supernova once the alert is sent [1].

There are two tiers of alerts, Gold and Silver, that go to different mailing lists. The Gold Alert is automated and includes all signed up astronomers, Sky & Telescope magazine, and the Hubble Space Telescope astronomers. The silver alert only goes to neutrino experimenters. Silver alerts are checked by experimental shift workers before the alert is sent out broadly. Both alerts include detectors involved, time of coincidence, and type of alarm for each experiment. Experiments can make announcements without restrictions, however for a silver alert they should specify that it is silver SNEWS alert [1]

Chapter 6

He-3 Prototype Counter Background Reductions and Results

Six prototype counters were obtained to test for backgrounds. The counters were made by two manufacturers who will remain unnamed due to proprietary reasons. These six counters were standard production proportional counters to see if the usual way of manufacturing them would meet the HALO-1kT background requirements. Four of these six had stainless steel bodies and He-3 in the gas composition, these four were taken underground at SNOLAB for preliminary data collection on the backgrounds. The other two were stored in the HALO office at Laurentian University. After that data collection was complete two of the four were chosen, one from each manufacturer with similar good initial results, for further data collection using electrostatic counters in the surface building at SNOLAB.

The following sections will discuss in detail the four prototype counters that were taken underground, explain how the initial data was collected as well as show that initial data and discuss it. After that, this chapter will detail what was altered on the counters to attach them to the electrostatic counters(ESC). Finally the results of the electrostatic counters will be discussed.

6.1 Prototype Counters in Detail

Previous students did simulations of various options for the counters before the purchase and initial data collection on the counters was done using the HALO backup DAQ system at Laurentian University. Gareth Smith did simulations of the choice of material of the counter's tube and its effect on gamma-related backgrounds. In HALO the counter tubes are subjected to a background gamma flux which can create Compton electrons and produce ionization in the proportional counters. Smith varied the tube wall material, the thickness of the tube wall, the gas composition, and the gas pressure to minimize the overlap of the gamma background events and the neutron window. However, it was impossible to entirely eliminate the gamma events in the neutron window. This work showed that aluminum gave lower gamma-related backgrounds than stainless steel above 50 keV. Smith also found that wall thickness had no effect on backgrounds and that either He-4 or argon could be added to the gas mixture. If argon was added there were fewer Compton scattered electrons whose deposited energy fell in the neutron window and were indistinguishable from the neutrons, than the original HALO counters had. If various amounts of He-4 were added to bring the gas pressure up to between 2.5 and 8 atm, the counter background would either match or have fewer events in the neutron window than the HALO counters depending on amount of He-4 added [47].

Ashley Stock did simulations to determine the alpha energy spectra of bulk and surface ^{222}Rn daughter contaminants. The simulations done on bulk and surface contaminants showed that surface ^{222}Rn contamination could easily be removed. It also showed that only alpha particles within 30 µm of the inner surface are not stopped by the wall and can leave ionization. Aluminum bodies allowed 1.5x more alpha particles through than stainless steel bodies due to its lower stopping power [48]. The simulation work on radon daughter products present in the detector bodies showed that only ^{210}Po would be observed in the detector bodies [49].

The counters that were taken underground will be referred to as HkT-1, HkT-2, HkT-3, HkT-4.

The other two counters that did not have any He-3 were not part of this research and thus were not numbered for this thesis. HkT-1 is from one manufacturer and has a SHV connector and a stainless steel body. Counters HkT-2, HkT-3, and HkT-4 are from the other manufacturer have 304 stainless steel bodies. These three counters have a brass silver plated SHV connector that is insulated by Teflon with an interior insulator of alumina ceramic. No percentages were given for gas composition, however there is only approximately 1% of a regular fill of He-3 in the gas composition to keep costs down for the prototype counters and so that the 764 keV neutron peak would be visible. What is known of the gas composition as well as the pressure and the recommended voltage range can be seen in Table 6.1.

Table 6.1: The manufacturer's specifications for the four counters.

Counter Name	Gases	Pressure [atm]	Recommended Voltage Range [V]
HkT-1	He-3, CF-4, He-4	2.5	1450 – 1700
HkT-2	He-3, He-4, CF-4	1.5	925 – 1475
HkT-3	He-3, He-4, CF-4	2.5	1225 – 1850
HkT-4	He-3, He-4, Ar, CO-2	2.5	900 – 1425

These counters were taken underground to determine background rates in the neutron window, this will be described in the following section.

6.2 Test Stand Measurements

Four counters were taken underground at SNOLAB to the HALO test stand. When HALO was built, extra channels were added to support the testing and calibration of NCDs as well as a test stand built to hold the NCDs while this was happening. This test stand is where the prototype counters were placed for preliminary data collection and can be seen in Figure 6.1. The preamp to the DAQ system from the test stand can be seen in Figure 6.2. Once set up there was some time spent to find the appropriate running voltage. For three of the counters this was easy as a co-op student had done some data collection with these counters previously. Settling on the proper voltage for HkT-4 was more difficult, this explains its shorter run time. The work on operating voltage determination was previously done by Kaouther Bouhedda [50], Itunu Osifeso [51], and

Julia Corcoran [52] during their respective undergraduate theses. The run lengths and voltages can be seen in Table 6.2.

Figure 6.1: The underground test stand for HALO counters. The counters were placed in each of the four tubes. For the calibration run the calibration source was placed in the middle of the tubes.

The background rate goal is 0.05 Hz in the full 4.3 km array of counters as described in Section 4.4. Once calibrated, a long run without a source was done to determine backgrounds, the length of which can be seen in Table 6.2. There were also 2 days 8 m 26s of data taken using the HALO Californium-252 calibration source. These runs were used to make sure the full 764 keV neutron

Figure 6.2: The preamp from the Test Stand to the DAQ system. Each chord is clearly labeled and colour coded.

Table 6.2: Run specifications for underground data collection

Counter Name	Run Length [d:h:m:s]	Operating Voltage [V]
HkT-1	119:17:56:17	1355
HkT-2	119:17:56:17	965
HkT-3	119:17:56:17	1255
HkT-4	97:0:26:40	840

peak position was known for the counters when analysis was done. The source was placed in the centre of the four counters, per Figure 6.1. The source was purchased in December 2010 from Frontier Technology. The source had 8.6 x 10^{-5} micrograms of ^{252}Cf, which has a half life, $T_{1/2}$, of 2.645 years. Based on an internal SNOLAB report the activity on Jan 1 2019, N(0), was expected to be 255 Bq. ^{252}Cf decays by both alpha-decay and spontaneous fission. The alpha branching ratio dominates but the alpha particles do not not escape the source and do not cause backgrounds. The spontaneous fission branch produces 3.8 neutrons per fission. On January 1, 2019 the source was producing 27.5 neutrons per second [53]. The calculation of the strength of the source on the day of the calibration run is shown in Equation 6.1. The calibration run was done from September 18 to September 20th, 2019. There were 8 months and 17 days between Jan 1, 2019 and Sept 18, 2019, or 0.7132 years, this is t. More information on the HALO ^{252}Cf source can be found in Colin Bruulsema's M.Sc. thesis [54].

$$\begin{aligned} N(t) &= N(0) \times e^{-\lambda t/T_{1/2}} \\ &= 27.5\ neutrons/second \times e^{-0.693 \times 0.7132y/2.645y} \\ &= 22.8\ neutrons/second \end{aligned} \tag{6.1}$$

Both the long test stand run and the calibration run data were rebinned to events per day per 50 keV with the position of the neutron peak being scaled to sit at 764 keV based on the calibration run results. The full test stand run data for each counter was scaled and was subtracted from the calibration data to ensure that we were seeing just the neutron source related events.

Table 6.3: Results of four counters test stand runs including calibration runs.

Counter	Full Run (551 keV to 1000 keV) [Events / day]	Calibration Minus Full Run (551 keV to 1000 keV) [Events / day]	Full Run Above 1000 keV [Events / day]
HkT-1	129 ± 11	2112 ± 46	610 ± 25
HkT-2	102 ± 10	818 ± 29	311 ± 18
HkT-3	280 ± 17	2152 ± 46	2044 ± 45
HkT-4	89 ± 9.4	896 ± 30	521 ± 23

The low energy contamination of the neutron window is high relative to the neutron capture related counts in the neutron window due to low amounts of He-3 in these prototype counters. Therefore, the neutron window was changed from 250 - 1000 keV to 551 - 1000 keV in order to avoid the low energy gamma backgrounds. On average counts per day in the neutron window have on the low end of 89 events per day, as shown in Table 6.3 giving 2.21 ± 0.23 Hz for the full 4.3 km of counters foreseen for HALO-1kT. In the following equations, Equation 6.2 and Equation 6.3, 4300 m is divided by 2 m because the prototype counters are 2 m long.

$$\begin{gathered} \frac{89 \pm 9.4\ \frac{\text{Events}}{\text{Day}}}{24\ \frac{\text{hrs}}{\text{Day}} \times 3600\ \frac{\text{s}}{\text{hr}}} = 1.03 \times 10^{-3} \pm 1.09 \times 10^{-4}\ \text{Hz} \\ 1.03 \times 10^{-3} \pm 1.09 \times 10^{-4}\ \text{Hz} \times \frac{4300\ \text{m}}{2\ \text{m}} = 2.21 \pm 0.23\ \text{Hz} \end{gathered} \tag{6.2}$$

On the high end the backgrounds are at 6.97 ± 0.42 Hz as seen in Equation 6.3.

$$\frac{280 \pm 17 \ \frac{\text{Events}}{\text{Day}}}{24 \ \frac{\text{hrs}}{\text{Day}} \times 3600 \ \frac{\text{s}}{\text{hr}}} = 3.24 \times 10^{-3} \pm 1.97 \times 10^{-4} \text{ Hz}$$
$$3.24 \times 10^{-3} \pm 1.97 \times 10^{-4} \text{ Hz} \times \frac{4300 \text{ m}}{2 \text{ m}} = 6.97 \pm 0.42 \text{ Hz} \tag{6.3}$$

With the goal of background rates due to internal radioactivity of 0.25 Hz in the full 4.3 km array of counters as mentioned in Section 4.4, these counters initial results show background between 8.9 and 27.9 times higher than the internal radioactivity goal. This is unacceptable.

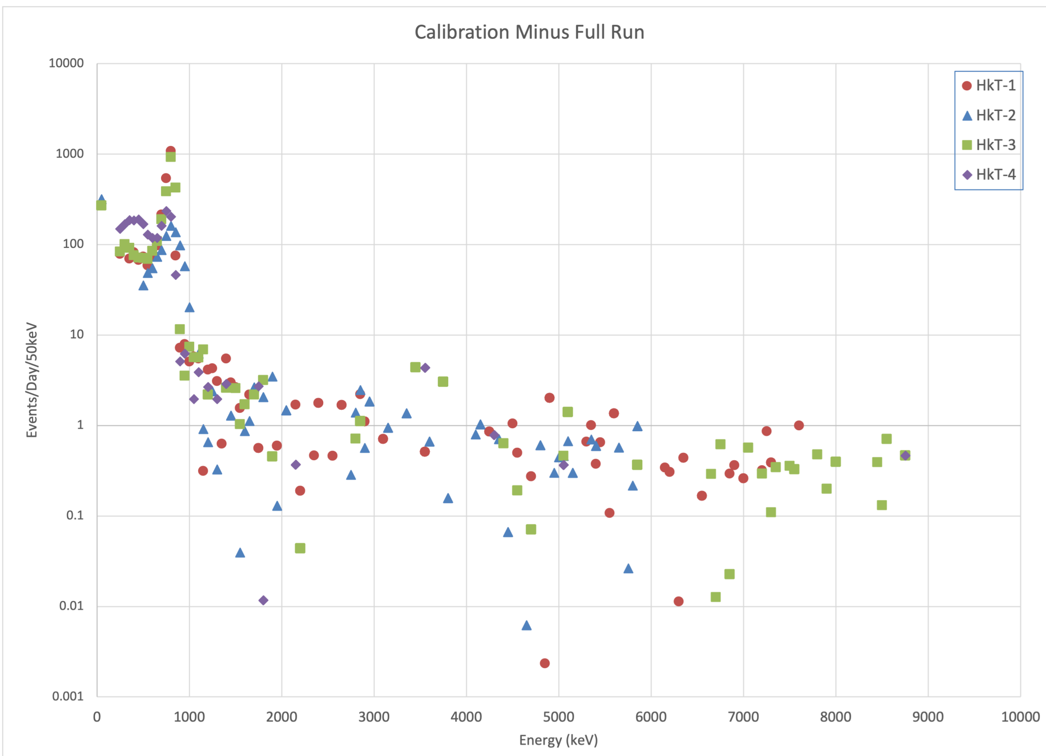

Figure 6.3: Calibration run minus the scaled full run to see the full neutron peak at 764 keV.

To establish the energy calibrations short runs were done with a Cf-252 neutron source present. A background subtraction was performed to more clearly see the 764 keV neutron capture peak. Figure 6.3 shows the data presented in Table 6.3. There is clear neutron peak on all four counters, particularly HkT-1 and HkT-3 have very distinct neutron peaks. Figure 6.4 shows a zoomed in

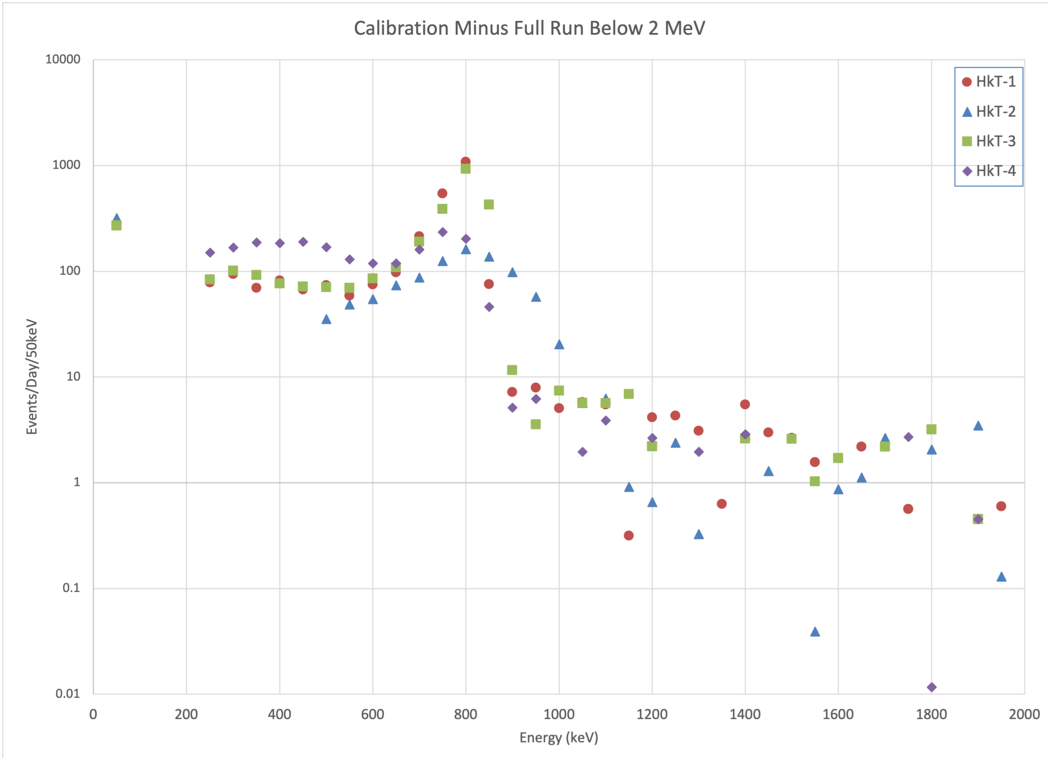

Figure 6.4: Zoomed in version of Figure 6.3 for data below 2 MeV focused on the neutron full energy peak. It is easy to see that HkT-1 and HkT-3 have similar counts, especially below the neutron full energy peak. HkT-4 has a different shape below the full neutron peak that is not fully understood. HkT-2 has significantly fewer events in the neutron full energy peak, as well as a different shape than expected.

version of the data focusing on the data below 2 MeV to more clearly see the backgrounds in the full neutron peak. They also peak at approximately the same Events/day/50 keV. The similarities in event rates as well as their similar specifications made them ideal candidates to do further research. HkT-4 was not a viable counter to do further background analysis on due to the lack of understanding of the strange shaping of events between 200 keV and 750 keV. HkT-2 could have been used but it had a less distinct neutron peak and less events per day in the neutron window. This led to choosing counters HkT-1 and HkT-3 for further research as they have similar event numbers when looking at the Calibration minus full run in the neutron peak. These two counters also have similar gas composition, pressure, and running voltages.

6.3 Assaying the Counters

Since the background rates are 8.9 to 27.9 times too high, assaying the counters is needed to better understand the sources. Backgrounds in the counters can come from various parts of the counters, including the wall bulk material, end caps, anode wire, inner walls, as well as exposure to radon in the air during the manufacturing process. In order to get more detailed information about which part of the counters the backgrounds are coming from, assaying the counters in stages is required. The initial assay stage was to prepare the counters to be connected with a vacuum seal to the electrostatic counters, ESC's, so the radon emanation rate of the stainless steel, or the bulk of the wall, could be measured. There were more ambitious plans to determine backgrounds in other parts of the counters however, due to external circumstances only the wall bulk material assay could be completed. To see the assay plans that were unable to be completed see Appendix A.3. The full procedure as used in the lab for autopsying the prototype neutron counters is in Appendix A.

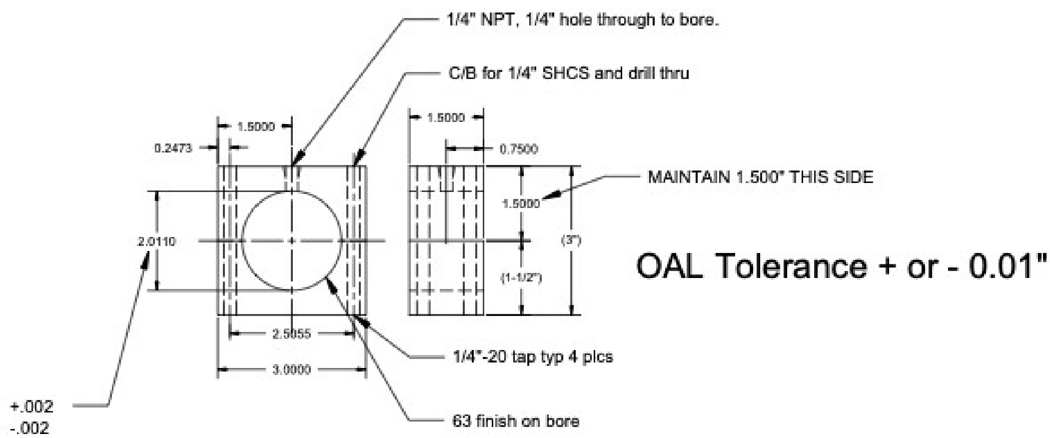

Figure 6.5: The final clamp diagram in auto-cad by SNOLAB engineers. The right side diagram shows the front view, where the counter will be placed, the channels for the screws to tighten the clamp, and the NPT hole that goes to the top of the counter. The left side of the diagram shows the side view, showing the channel placement and the NPT hole placement.

Before they could be connected to the ESC system clamps needed to be fabricated so the neutron counters could be attached to the electrostatic counters. I designed the clamp and the integration team at SNOLAB was able to draw up a proper drawing in auto-cad, as seen in Figure 6.5, and then machine the four clamps.

The only change to the procedure was that the clamps were attached with vacuum grease on the bolts to prevent seizing. Figure 6.5 is of the counter right before the clamp was attached, with the hole drilled in and indium wire around the hole to form a vacuum seal between the counter and the clamp. The vacuum seal is required as the ESC's require a vacuum before they fill with the carrier gas, ESC's are explained more fully in Section 6.4.

Figure 6.6: The counter after a hole has been drilled with the indium wire around the hole so the clamp will seal to the counter

Figure 6.7: The image on the right is of a clamp attached to a counter with the photo taken from then end of the counter. The image on the right is the same clamp attached to the same counter but the photo is taken from the top.

6.4 Counting the Bulk Material

Electrostatic Counters detect ^{220}Rn and ^{222}Rn daughters with very high efficiency. Originally developed for the SNO detector to measure radon emanation rates from various materials, its initial success led to a redesign with higher sensitivity and efficiency for further radon measurements.

A diagram of the ESC loop can bee seen Figure 6.8. the loop from the sample, in this case the prototype counters, to the ESCs through the pump and back to the sample is initially filled and evacuated several times with N_2. The loop is then filled with dry N_2 to 26 ± 1 mbar to act as carrier gas to transport the Radon from the sample to the ESCs. The alpha detector in the ESC detects positive polonium ions from radon decay due of the shape of ESC chamber. The output of the alpha counter is amplified and digitized in 1024 channels which are written every 3 hours to a disk [55].

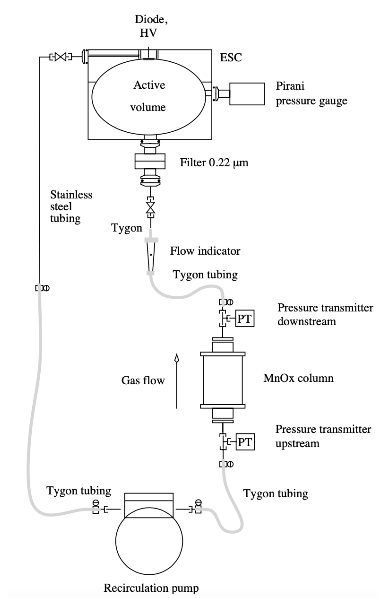

Figure 6.8: The diagram of gas flow, in the diagram the prototype counters for this research is shown as “MnOx column” [56].

Once the two counters were cleaned, had holes drilled into them, and had clamps attached, the clamps were leak tested using a Helium leak detector and found to be able to hold vacuum without helium getting into them, the leak testing set up can be seen in Figure 6.9. They were then counted using the electrostatic counters at SNOLAB with the help of Dr Jacques Farine and Jéan-François Menard. The counters were attached to the ESC frame and connected to the ESCs using Tygon tubing.

Figure 6.9: A prototype counter with clamp attached. It has a Tygon tube going in attached to a Helium leak detector that can be seen on the floor in the top right corner of the image.

For both counters there needed to be a sample run and a blank run, the blank run then needs to be subtracted from the sample run. The blank run is a run done where the counters are detached from the ESCs and replaced with a small adaptor and counted again, the adaptor was a couple inch piece of 3/8" OD SS tubing. The configuration of the ESCs was not changed between the sample and blank runs.

Extensive training is required to operate the ESCs and as there were only two samples being taken it was decided to have Dr. Farine and Mr. Menard do the ESC data collection with an initial report being released in November 2021, however HkT-1 had inconsistent results which meant the sample and blank run had to be retaken with a final report released in May 2022. Data during the run is compiled and stored in a 1024-bin energy spectrum and every 3 hours that data is saved to a disk. The DAQ and pump run independently so the circulation of carrier gas is constant. The HkT-3 sample run was accidentally stopped during the counting, however the stop was noticed and the DAQ restarted.

The emanation rate was calculated using Equation 6.4, where H is the final emanation rate of the prototype counters.

$$H = \frac{1}{TE_S}\left(S - \left[\left(\frac{B}{VE_{dyn,B}} - R_B\right) + R_S\right] \cdot VE_{dyn,S}\right) \tag{6.4}$$

B and S are the blank and sample activities given by the FITESC software[1] $VE_{dyn,B}$ and $VE_{dyn,S}$ are the blank and sample dynamic volume efficiencies. TE_S is the volume and transport efficiency for thoron(^{220}Rn) for the sample, for ^{222}Rn $VE_{dyn,S}$ plays this role. R_S and R_B are the lab air ^{222}Rn ingress rates for the sample and blank runs. Thoron, ^{220}Rn, leaking in from the outside of the counters is not a concern, only the longer lived radon, ^{222}Rn.

^{222}Rn ingress rates in the lab air needed to be taken into account when doing the final calculations. When these measurements were taken there was no ambient radon counter in the room, but there were counters in the Clean Room Hallway and Research Lab B. It was assumed the radon concentration in the counter room was similar to the other two rooms. The radon ingress correction depended on the leak rate and concentration of radon in the air so this number varies for each run. The results are shown in Table 6.4.

Counter	^{220}Rn/day	^{222}Rn/day	^{220}Rn/m^2 day	^{222}Rn/m^{2}day
HkT-1	19 ± 4.6	5.5 ± 21	63 ± 15	18 ± 68
HkT-3	13 ± 3.1	33 ± 14	43 ± 10	110 ± 49

Table 6.4: HALO ESC results

Equation 6.2 was used to get translate emanation rates in the individual counters to what the emanation rates will be in the full 4.3 km detector. The results for both counters initial underground run in both the 2m counters and 4.3 km and the ESC runs propagated in 4.3 km are shown in the Table 6.5.

[1]FITESC gives the activities measured in the active volume of the counter "The FITESC results provide the activities as measured in the ESC chamber, the active volume of the counter."

Counter	Underground results		ESC Results	
	Backgrounds in 2m Counters [Hz]	Backgrounds in 4.3 km [Hz]	^{220}Rn in 4.3 km [Hz]	^{222}Rn in 4.3 km [Hz]
HkT-1	1.49 x 10^{-3} ± 1.27 x 10^{-4}	3.21 ± 0.27	0.47 ± 0.11	0.14 ± 0.52
HkT-2	1.18 x 10^{-3} ± 1.16 x 10^{-4}	2.54 ± 0.25	N/A	N/A
HkT-3	3.24 x 10^{-3} ± 1.97 x 10^{-4}	6.97 ± 0.42	0.32 ± 0.077	0.82 ± 0.35
HkT-4	1.03 x 10^{-3} 1.09 x 10^{-4}	2.21 ± 0.23	N/A	N/A

Table 6.5: Initial results compared to ESC results

The radon backgrounds results are 2.7 to 16.4 times higher than the goal required for the individual components. Other experiments have also gone through the process to test and find the cleanest material, an example being XENON1T who put a paper out on their findings for ^{222}Rn emanation rates. XENON1T found their cleanest stainless steel to emanate 9 ± 4 μ Bq/m^2 and their dirtiest to emanate 560 ±100 μ Bq/m^2 [57]. Which is 0.78 ± 0.35 ^{222}Rn /m^{2}day and 48 ± 9 ^{222}Rn /m^{2}day, the conversion can be seen in Equation 6.5. Comparing to Table 6.4 HkT-1 is in the same range for ^{222}Rn as the XENON1T results, HkT-3 has more than double the ^{222}Rn emanation than the highest from the XENON1T paper.

$$\begin{aligned} 1\mu Bq &= \frac{1\ event}{10^6\ seconds} \\ 1day &= 86400\ seconds \\ event &= {}^{222}\text{Rn}\ event \\ 9 \pm 4\ \frac{\mu Bq}{m^2} &= 9\ \frac{Rn}{10^6\ seconds} \times 86400\ \frac{seconds}{day} \\ &= 0.78 \pm 0.35 \frac{Rn}{m^2 day} \end{aligned} \tag{6.5}$$

Chapter 7

Conclusions

A supernova is a once in a lifetime opportunity to learn more about the universe. SNEWS 2.0 plans to take advantage of that opportunity to learn from both the never before seen early visual data that the astronomers can provide as well as the neutrino data that particle physics experiments can provide. However, most particle physics experiments have goals other than supernova detection, so having an experiment that is dedicated to supernova detection would ensure that a supernova is not missed. HALO-1kT can be that experiment with goals of high uptime and low maintenance, that have already been proven possible with HALO, but having much better event statistics and an ability to see a supernova that happens much further away.

The supplied prototype counters while they are not bad in terms of cleanliness they are not good enough to meet the goals of HALO-1kT. There are improvements that can be made and tested and it is possible to get to the goal although the price will go up with cleaner counters. The two final counters have comparable ^{220}Rn emanation rates of 0.47 ± 0.11 Hz for HkT-1 and 0.32 ± 0.077 Hz for HkT-3. Although HkT-3 has nearly 6 times the ^{222}Rn emanation rates, 0.82 ± 0.35 Hz, than HkT-1, 0.14 ± 0.52 Hz as seen in Table 6.5, these all are larger than the goal of 0.05 Hz required to provide a SNEWS trigger with sensitivity to the entire galaxy and an acceptably low false alert rate. To compare to other experiments, XENON1T results range from 0.78 ± 0.35 ^{222}Rn /m^{2}day to 48 ± 9 ^{222}Rn /m^{2}day [57], the prototype counters range from the middle of the two to double the XENON1T backgrounds, this can be seen in Table 6.4.

Further work can be done to determine what the background levels are in each part of the counters. Specifically interesting is the anode wire, the inner wall material, and the end caps. Both the anode wire composition and the end cap components are proprietary so the backgrounds cannot be easily determined using calculations. Another future project is to coat the inner surface of the counters with approximately 30 μ of ultra-pure C1011 copper, ideally by copper electro-plating as that will prevent alpha particles that originate from the wall from reaching the gas and creating an event.

To count the proprietary anode wire it will first need to be carefully removed from the counter. The anode wire is probably made of copper or tungsten, possibly gold plated, and can be dissolved in acid and then counted using an ICPMS. The Perdue Analytic Facility at Laurentian University[1] has one of these machines that has a limit of 2.5 ppb assuming 10 mg of wire. There is also, in the Earth Sciences department at Laurentian, a triple quadrupole ICPMS that has greater sensitivity than the one in the Perdue Analytic Facility. There are people at SNOLAB who have access to the Perdue Analytic Facility and may be able to do this analysis in future if decided it is needed.

The end caps can be counted using the electrostatic counters if placed in a pre-counted container. They can easily be removed from the counters using the HALO NCD cutter as seen in the procedure. Finally, to count the inner wall material, the inner wall needs to be acid etched. Once the acid etching is done the acid can be counted. Further consultation with the analytical chemists would be needed to determine the best way to count the acid. Possible ways of counting could be using an ICPMS or the background counting experiments at SNOLAB.

Beyond determining backgrounds in other components of the counters other ways of decreasing the backgrounds would be to use cleaner stainless steel, copper plate the inner walls of the counters, as well as using cleaner materials for the end caps and anode wire. The copper plating is possible and SNOLAB is in the process of planning a copper plating facility at the lab which would help in keeping costs down. Using cleaner materials for the end caps and anode wire is more difficult

[1]More on the Perdue Analytic Facility can be found at the university website: `https://laurentian.ca/perdue-central-analytical-facilty` and `https://laurentian.ca/research/pcaf`

without knowing what the material composition is of the end caps and anode wire.

Once the decision for copper plating and cleaner materials is made, and new prototype counters are made, further testing can be done to determine if the backgrounds achieve the goal to meet SNEWS requirements and the detector as a whole would be able to see a supernova across the galaxy.

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Appendix A

Procedure for Autopsying and Counting the Prototype Counters

A.1 Pre-amble

This procedure proposes how to autopsy the prototype counters and count the backgrounds of the various parts of the counters.

A.1.1 Clamp

The clamps will attach to the prototype counters so that they can be attached to the Electrostatic counters. We will need two clamps per prototype counter that we decide to autopsy, at minimum four clamps as we are planing on autopsying at least one counter from each vendor. The idea for the clamps is that it goes around the counter and attach to the stand for the electrostatic counter. The connector from the clamp to the electrostatic counter will be Swagelok part SS-600-1-4 to SS-601-PC. The diameter for the hole in the clamp for two of the four clamps needs to be 2.0115" and for the other two clamps needs to be 2.0112".

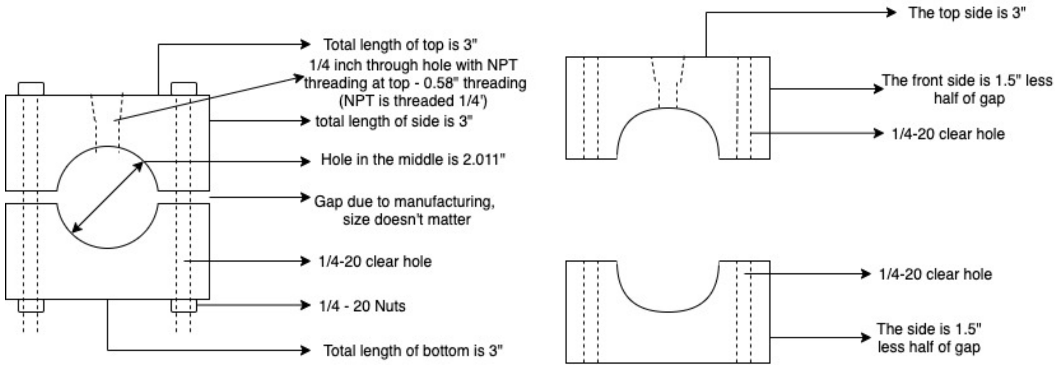

Figure A.1: Front View of Clamp

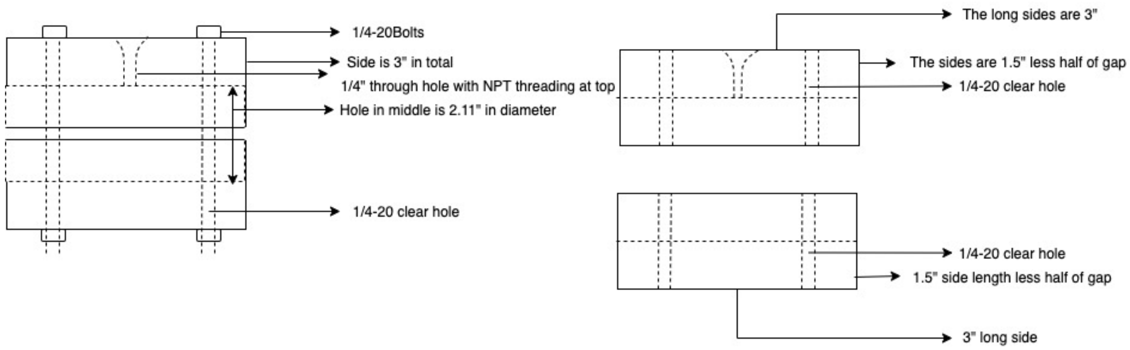

Figure A.2: Side View of Clamp

A.2 Procedure

A.2.1 Cleaning the Outer Surface of the Prototype Counters

The outer surface needs to be cleaned before a hole is drilled into the counter as any particles that are on the outer surface are not of interest to the backgrounds. It is probable that any surface contaminants will get inside the counter when drilling the holes as the drill will go into the counter forcing any outer surface contaminants inside.

Materials and supplies:

- Counters(2)
- Ziplock bags(4)

- Methanol
- Radiac wash
- UltraPure water
- Nitrile gloves
- Paper to cover the table (either large kimwipes or the rolls that are in the surface clean rooms)
- Kimwipes
- Swipe test kit

This section only requires one person, starts in the surface car wash

- ☐ In the surface car wash at SNOLAB
- ☐ Cover tables in either Kimwipes or clean room paper
- ☐ Place Counters on table carefully to block them from rolling off the table - can use a box
- ☐ Put on gloves
- ☐ Using UPW and Kimwipes clean the entire surface of both counters
- ☐ Use methanol and Kimwipes to dry
- ☐ Change gloves
- ☐ Do a swipe test
- ☐ If the swipe test passes skip the following step and substeps
- ☐ If the swipe test does not pass:
  - ☐ Using a diluted cleaner(from the carwash) clean the counters
  - ☐ Wipe with UPW
  - ☐ Dry with methanol

- ☐ Swipe test
- ☐ If passed continue, if not repeat these steps until it passes

☐ Move into the clean room antichamber

☐ Put counters on table, careful to block from rolling

☐ Take off outdoor shoes

☐ Put on clean room suit

☐ Put on hairnet, safety glasses, clean room boots

☐ Put on gloves

☐ Take counters into clean lab - first lab on the left

☐ Put counters on a covered table, careful to block them from rolling

☐ Fill Ultrasonic cleaner with UPW and a bit of radiac wash

☐ Bring Ultrasonic cleaner to temperature

☐ Put counters in Ultrasonic

- ☐ Only one end of the counter will fit
- ☐ If possible put both counters in the ultrasonic
- ☐ The lid of the ultrasonic will NOT go on

☐ Start Ultrasonic cleaner and let run for 1hr

☐ If staying in the room put in earplugs

☐ When done, drain ultrasonic cleaner, there is a hose and pump

☐ Fill ultrasonic cleaner with UPW

☐ Heat up Ultrasonic

- ☐ Start ultrasonic and let run for 45 min
- ☐ If staying in the room put in earplugs
- ☐ When done, drain ultrasonic cleaner, there is a hose and pump
- ☐ Fill ultrasonic cleaner with UPW
- ☐ Heat up Ultrasonic
- ☐ Start Ultrasonic and let run for 30-45min
- ☐ As this last rinse is running:
  - ☐ Get methanol
  - ☐ Cover table in clean paper
  - ☐ Get ziplocks
  - ☐ Put on clean gloves
- ☐ When ultrasonic is done
- ☐ Take out one counter
- ☐ Wipe cleaned end of counter with methanol
- ☐ Put ziplock on clean end and seal
- ☐ Put counter on the clean table, blocking to prevent rolling
- ☐ If the second counter was in the ultrasonic, take it out of the ultrasonic
- ☐ Wipe cleaned end of counter with methanol
- ☐ Put ziplock on clean end and seal
- ☐ Put counter on the clean table, blocking to prevent rolling
- ☐ Drain Ultrasonic

- ☐ Do all again for the other ends:
- ☐ Fill Ultrasonic cleaner with UPW and a bit of radiac wash
- ☐ Bring Ultrasonic cleaner to temperature
- ☐ Put counters in Ultrasonic
  - ☐ Only one end of the counter will fit
  - ☐ If possible put both counters in the ultrasonic
  - ☐ The lid of the ultrasonic will NOT go on
- ☐ Start Ultrasonic clean and let run for 1hr
- ☐ If staying in the room put in earplugs
- ☐ When done, drain ultrasonic cleaner, there is a hose and pump
- ☐ Fill ultrasonic cleaner with UPW
- ☐ Heat up Ultrasonic
- ☐ Start ultrasonic and let run for 45 min
- ☐ If staying in the room put in earplugs
- ☐ When done, drain ultrasonic cleaner, there is a hose and pump
- ☐ Fill ultrasonic cleaner with UPW
- ☐ Heat up Ultrasonic
- ☐ Start Ultrasonic and let run for 30-45 min
- ☐ As this last rinse is running:
  - ☐ Get methanol
  - ☐ Cover table in clean paper

- ☐ Get ziplocks
- ☐ Put on clean gloves

☐ When ultrasonic is done

☐ Take out one counter

☐ Wipe cleaned end of counter with methanol

☐ Put ziplock on clean end and seal

☐ Put counter on the clean table, blocking to prevent rolling

☐ If the second counter was in the ultrasonic, take it out of the ultrasonic

☐ Wipe cleaned end of counter with methanol

☐ Put ziplock on clean end and seal

☐ Put counter on the clean table, blocking to prevent rolling

☐ Drain Ultrasonic

A.2.2 Drilling the hole

Drilling the holes in the counters will be difficult as we want to do it in such a way as to get as few particles from the outer surface inside the counter as possible. The drilling will be done after we etch the outer surface so we can assume that any particles from drilling that do get inside of the counter are from the bulk material, even so we want to minimize particulates inside the counter. There is a clamp underground in the HALO area specifically for NCDs that would work for the prototype counters, this needs to be brought to surface.

This Procedure requires a second person to hold a vacuum

- Tables and Clamps from HALO area underground
- Cleaned counters

- Nitrile Gloves
- Drill
- Tungsten carbon drill bit
- Vacuum
- 1/4” center punch
- Hammer

☐ If the tables and clamps were double bagged removed the bags and do a swipe test

☐ If the tables and clamps were not double bagged OR if it did not pass the swipe test:

  ☐ Put on gloves

  ☐ Using a diluted cleaner(from the carwash) clean the counters

  ☐ Wipe with UPW

  ☐ Dry with methanol

  ☐ Swipe test

  ☐ If passed continue, if not repeat these steps until it passes

☐ Move into the clean room antichamber bringing the table and clamps with you

☐ Take off outdoor shoes

☐ Put on clean room suit

☐ Put on hairnet, safety glasses, clean room boots

☐ Put on clean gloves

☐ Take tables and clamps into the clean lab

☐ Put a counter in clamps securely

☐ Put second counter on a covered table, carefully blocking it from rolling

☐ Take ziplock off one end

☐ Using 1/4” centre punch, punch an indent 3” from the end

☐ Turn counter so indented spot is on the bottom - towards the ground

☐ Second gloved person turn on vacuum and hold towards indent

☐ Drill into indent until through the wall but not through whole counter

☐ Cover hole end with a new ziplock

☐ Carefully put this counter on a covered table, blocking from rolling

☐ Repeat Steps for other end of first counter and for both ends of the other counter:

  ☐ Put second counter in clamps securely

  ☐ Take ziplock off one end

  ☐ Using 1/4” centre punch, punch an indent 3” from the end

  ☐ Turn counter so indented spot is on the bottom - towards the ground

  ☐ Second gloved person turn on vacuum and hold towards indent

  ☐ Drill into indent until through the wall but not through whole counter

  ☐ Cover hole end with a new ziplock

A.2.3 Attaching the Clamps

To attach the clamps you need:

- Clamps (2 per counter)
  - 4 bolts per clamp - 16 total
  - 4 nuts per clamp - 16 total

  - 8 washers per clamp - 32 total

- Counter
- Indium wire
- Ziplocks
- Gloves
- HALO Tables and Clamps

This takes place in the clean room on surface, it might require two people to do

☐ Put on clean gloves

☐ Place indium wire around the hole drilled into the counter counter to be sandwiched in between the counter and the clamp, careful not to put any over the hole

☐ Line up the clamp with the counter so the hole in the counter lines up with the 3/8 OD port connecter.

☐ By hand sandwich the clamp so the indium wire isn't covering the hole and the hole in the counter lines up with the hole in the clamp

☐ Screw the clamp down so the indium wire gets compressed for all four bolts

☐ Repeat for other end of counter and the second counter

A.2.4 Electrostatic Counters

Once the counters and the clamps are attached together, with Jacques' approval and help, attach the counters the Jacques' system on surface at SNOLAB. Once they are attached they can be counted.

A.2.5 Cutting off the Ends and taking out the anode wire

After we are done counting using the electrostatic counters it is time to cut off the ends.

- Gloves
- HALO NCD cutter
- Ziplock bags
- Wire cutter
- Table covers - either the papers in the clean lab or Kimwipes

☐ Put on gloves

☐ Cover a table in clean paper

☐ Using the HALO NCD cutter cut 4 inches from the end or after the clamps

☐ The anode wire will probably snap when the ends come off but if it does not cut off the wire carefully with clean tools.

☐ Put the removed end cap on a clean table

☐ Cut off the other end 4" from the end or after the clamp using the HALO NCD cutter

☐ The anode wire will probably snap when the ends come off but if it does not cut off the wire carefully with clean tools.

☐ Put the second removed end cap on a clean table

☐ Once the wire is cut on both ends remove it from the counter, and place it in a ziplock bag until it is at the place to determine the composition of the wire.

☐ Then end caps should also be place into a ziplock bag until they get counted.

☐ Repeat these steps for the second counter

A.3 Future Steps

A.3.1 Counting the anode wire

Once the anode wire has been cut from the end caps and taken out of the counter it is time to count the wire itself. As the wire composition is proprietary, we don't know what the anode wire material is, although it is probably made of copper or tungsten, and possibly gold plated. We can talk to Bruce and Ian about this or contact the chemistry department, although the later will probably be more difficult with Covid-19. For counting the wire, I contacted Heather Dufour at the Perdue Analytic Facility in the Cliff Fielding Building, I was informed their ICPMS, using their standard method, would have a limit of 2.5 ppb assuming there is 10mg of wire.

A few things to note about this, first, the 10 mg is based off of a back of envelope calculation, so it could be more or less. Secondly if we need more sensitivity Jeff Marsh in the Earth Sciences department in the Willet Green Miller has a triple quadrupole ICPMS that is much more sensitive. The final thing to note is the method to use the ICPMS would dissolve the wire, so there could only be one measurement(per counter we are willing to sacrifice). We could also talk to the chemistry department and see if they have a method of determining the material without destroying it before we send it to the ICPMS so we could know for sure what material(s) it is made out of and be able to determine if there is a better option out there.

A.3.2 Counting the inside wall material

To count the inner wall material we will acid etch the inner wall. In order to get the entire inner wall of the counter we could stand the counter up on one end in a bucket, using a stand, and pour acid down into the counter, letting the acid stay in the counter a few days. For this the counter would need a solid container to stand in as well as a cover so nothing falls into the acid while it is leeching. Once enough time has passed for the acid to leech the inner wall, we can count the particles in the acid. Consulting with the analytical chemists to determine the best way of counting the acid would be required.

A.3.3 Counting the end caps

Options for counting the end caps would be using electrostatic counters. If we use electrostatic counters, we can put the end caps into a pre-counted container and attach them to the system and count them that way.

Curriculum Vitae

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Laurentian University

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Related Work Experience

Teaching Assistant

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Publications:

C. Amole et al. (PICO Collaboration). (2019). Data-driven modeling of electron recoil nucleation in PICO C3F8 bubble chambers. Physical Review D, DOI: 10.1103/PhysRevD.100.082006

C. Amole et al. (PICO Collaboration). (2019). Dark matter search results from the complete exposure of the PICO-60 C3F8 bubble chamber. Physical Review D, DOI: 10.1103/PhysRevD.100.022001

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Presentations and Posters:

The 3rd Summer Particle Astrophysics Workshop(Art McDonald had a farm, EIEIO) 2021, SNEWS and HALO, presentation

CAP Congress 2021, Low Background Neutron Counters for HALO-1kT, poster

SNEWS 2.0 Workshop, poster

HALO-1kT Sudbury 2019 collaboration meeting, SNEWS Considerations, presentation

SNOLAB Summer Student Talks 2018, PICO Summer 2018, presentation

SNOLAB Summer Student Talks 2017, Neutron Flux, presentation