Characterization of the MARS Neutron Detector

by

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Calvin Howell

Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Department of Physics in the Graduate School of Duke University

2021
ABSTRACT

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Abstract

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) was first measured by COHERENT in 2017 nearly 40 years after it was first proposed. The process involved measuring tiny nuclear recoils that result from a neutrino scattering off of atomic nuclei. COHERENT made the first two measurements of CEvNS at the Spallation Neutron Source (SNS) and is working toward additional measurements there with the goal of observing the dependence of the cross section on detector material. The SNS, as the name implies, is an intense neutron source. These neutrons must be fully accounted for as a background for CEvNS because they are coincident with the neutrinos and because they can leave a similar recoil signature in detectors.

The Multiplicity And Recoil Spectrometer (MARS) was deployed at the SNS to measure neutrons. MARS takes advantage of capture-gating to identify neutrons separate from other environmental backgrounds. In order to measure neutrons at the SNS, MARS must be characterized there to assess detection efficiencies and performance. The detection efficiency for MARS was determined to be 3.9% for 14 MeV neutrons and is a function of cuts on the variables characteristic to the capture-gating method.

In this work, other characterization measurements are detailed including trigger efficiency, light yield and resolution as a function of position, and neutron detection efficiency. A first measurement of the neutron fluence with MARS is described for its original location in Neutrino Alley. After determining cuts on the relevant variables, 179 ± 27 neutrons are used to measure a fluence of 415 neutrons/m²/10¹² J ±15%_{stat} + ±54%_{sys} of protons on target. This fluence is expectedly lower than previous measurements with other detectors as MARS was in a more neutron-quiet location. A first look at the deposited energy spectrum from these neutrons is also shown.
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I grew up playing and loving team sports. Wins are sweeter and losses are easier when you are part of a team. The culmination of this Ph.D. experience is an even sweeter one for me in large part due to the people I have had working with me along the way. I could not be more grateful than I am for each and every one of them.

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Chapter 1

Introduction

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) was first measured by the COHERENT collaboration in 2017. The measurement process involves identifying tiny nuclear recoils that result from the neutrino scattering on atomic nuclei. This requires very sensitive detectors that operate with low background rates.

Neutrons can interact in the detector to produce signals which mimic the CEvNS signals. Neutrons are especially challenging as a background because CEvNS measurements are oftentimes performed near intense neutrino sources which are also intense neutron sources. A proper characterization of the neutron background is essential for any CEvNS measurement.

COHERENT performs its CEvNS measurements at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The SNS provides an intense, pulsed source of neutrinos for the CEvNS experiments but also is an intense neutron source. These neutrons are coincident with the neutrinos and are therefore a potentially problematic background source.

The Multiplicity And Recoil Spectrometer (MARS) was deployed to the SNS in 2017 to characterize the neutron backgrounds. MARS is a gadolinium-doped plastic scintillator which takes advantage of the neutron capture to identify neutron interactions in the detector. The work focuses on characterization measurements of the detector which are necessary for neutron background measurements. Additionally, a first analysis of the neutron fluence and recoil spectrum is shown.

Chapters 2 and 3 detail the neutrino and neutron processes which are relevant
in CEvNS measurements. This includes a description of CEvNS and the neutrinos needed for the process to occur. Neutron processes which mimic CEvNS are described in Chapter 3 as well as those used in neutron measurements.

In Chapter 4, the SNS site for COHERENT experiments is described. Then is Chapter 5, the COHERENT detectors at the SNS are detailed. This includes the detectors used to make the first two measurements of CEvNS as well as the other CEvNS detectors and other measurements which are ongoing.

Chapter 6 includes a description of MARS. In addition to a description of the hardware in MARS, a detailed look at how the data acquisition works is provided. This includes the capture-gating method used to identify neutron signals.

In Chapter 7, the characterization measurements performed at the SNS are described. This includes measurements of trigger efficiency near threshold, light yield and resolution, and neutron detection efficiency. All of these characterization measurements play a role in neutron measurements with MARS.

Chapter 8 includes a first analysis with MARS of the SNS neutrons. The selection process is described which is used to identify neutrons in the data. The neutron fluence is shown over time and a look at the recoil spectrum is included. Chapter 9 is a summary of the results from this work.
Chapter 2

NEUTRINOS AND COHERENT SCATTERING

Neutrinos have been a source of great experimental interest since they were proposed by Pauli to explain problems with beta decay experiments. Initially they served as a convenient and unfortunate solution to the problem with missing energy in beta decay. They were convenient because they would have all the properties needed to explain the problem: light, neutral, and difficult to detect. They were unfortunate because the scale and technological requirements of experiments needed to detect them seemed beyond possibility. As technologies developed, however, what previously seemed impossible suddenly became reality. This has been the story of neutrinos from the beginning. As technologies improve, more and more is learned about this mysterious particle. Even now in 2021, better and better tools are being developed to learn even more about neutrinos and their role in the universe.

2.1 NEUTRINO INTERACTIONS

The Standard Model describes the neutrino as a weakly interacting, neutral particle. Weakly interacting means that interaction cross sections, a primary driver for event rates, are going to be quite small. These cross sections can be as small as $10^{-38}$ cm$^2$ or smaller. This means any neutrino experiment will require many neutrinos, a large mass, or both to produce a measurable event rate. Neutral particles are also challenging because they do not interact electromagnetically. Many modern detectors rely on
electromagnetic interactions for detection signals. In fact, many neutrino detectors rely on electromagnetic interactions for detection signals, though those interactions are from secondary particles because the neutrino does not interact electromagnetically.

The two primary channels for neutrino interactions are the charged-current channel and the neutral-current channel as in Figure 2.1. Neutrinos come in three flavors, and those three flavors are the same three flavors of charged leptons in the Standard Model - electron, muon, and tau. The three flavors of neutrinos are the electron neutrino, the muon neutrino, and the tau neutrino. A charged-current interaction is one in which the neutrino interacts through the exchange of a charged W boson. The neutrino will interact with its leptonic partner particle. In the charged-current interactions, the detection signal will be a scattered charged lepton. In neutral-current interactions, the neutrino interacts through the exchange of a neutral Z boson. This is the way in which neutrinos elastically scatter off of leptons or even nuclei.

Most neutrino experiments search for neutrino interactions with leptons. The reason for this is that those interactions can produce a recoiling lepton. For example, when an electron neutrino elastically scatters off of an electron, that electron gains momentum. Detecting energetic electrons has been done for over 100 years. Detector technologies for this purpose have been improved over many decades. Electrons are relatively easy to measure when compared to other Standard Model particles.
Positrons are also very easy to measure because they interact readily in matter. Inverse beta decay (IBD) is the process in which an electron antineutrino interacts with a proton to produce a positron and a neutron,

$$\bar{\nu}_e + p \rightarrow e^+ + n^0.$$ (2.1)

Most of the best-known neutrino detectors involve detection of neutrinos via positron production which is shown in Figure 2.2.

**Figure 2.1:** Feynman diagrams of the neutral-current (left) and charged-current (right) components of a neutrino scattering on an electron.

**Figure 2.2:** Feynman diagram of inverse beta decay (IBD).
Figure 2.3: Neutrino cross sections vary by interaction channel and target. Those cross sections are very small, but CEvNS stands out as the largest at relevant energies. Neutrino-induced neutron (NIN) cross sections on lead are also relatively large. Cross sections for neutrino scattering on iodine, inverse beta decay, and neutrino-electron scattering are several orders of magnitude smaller than CEvNS in this energy range [2].

A more challenging detection channel is to measure neutrino interactions on nuclei. This interaction can be elastic or inelastic. In elastic interactions, again, a recoiling mass (in this case a nucleus) is the event signature. Recalling nuclei are much more difficult to measure than recoiling leptons because the kinetic energy change is so much smaller in the nuclear case. Signals are typically proportional to the energy of the signal particle. For inelastic interactions, signatures may be deex-
citation gammas or ejected nucleons.

Most neutrino experiments are done with very large detector volumes and are done over long periods of time. Alternatively, an experiment can be done in close proximity to an intense neutrino source, such as a nuclear reactor. In both cases, background exposure can be challenging to manage in analysis.

Figure 2.3 shows cross sections for several neutrino interactions. The charged-current interactions in red and green are orders of magnitude smaller than the neutral-current interactions in black and blue. This enhancement exists in the energy ranges shown, but for energies much higher than this range the charged-current interaction cross sections begin to dominate.

2.2 COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

The Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) process was postulated in 1974 as a direct consequence of other observations of neutral-current neutrino interactions on nuclei\[8, 9\]. It was natural to assume that neutrinos with wavelengths approximately equal to nuclear diameter lengths could scatter coherently off of the entire nucleus instead of off the individual nucleons. For a medium-size nucleus:

\[ E_\nu \lesssim \frac{hc}{R_N} \lesssim 50\text{MeV} \]  

\( E_\nu \) is the neutrino energy and \( R_N \) is the radius of the nucleus. This process would have a significantly larger cross section because of the implied coherence. The chal-
The challenge in detecting this interaction is that since it is a neutral-current interaction, and thus no charged lepton, then the signal is a recoiling nucleus. These nuclear recoils are low enough in energy to be undetectable in all but the most sensitive detectors.

2.2.1 NEUTRINOS IN COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

Given the size of atomic nuclei, the CEvNS process would be expected to occur for neutrinos with energies $\mathcal{O}(10 \text{ MeV})$. The differential cross section is given by\cite{10}:

$$
\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \left\{ (G_V + G_A)^2 + (G_V - G_A)^2 (1 - \frac{T}{E_\nu})^2 - (G_V^2 + G_A^2) \frac{M T}{E_\nu^2} \right\} \quad (2.3)
$$

where $T$ is the energy of the recoiling nucleus, the Fermi coupling constant $G_F = 1.1663787(6) \times 10^{-5} \text{ GeV}^2$, $M$ is the mass of the nucleus, $E_\nu$ is the neutrino energy. The vector ($G_V$) and axial ($G_A$) couplings are:

$$
G_V = (g^p_V Z + g^n_V N) F_{nuc}^V(Q^2) \quad (2.4)
$$

$$
G_A = (g^p_A (Z_+ - Z_-) + g^n_A (N_+ - N_-)) F_{nuc}^A(Q^2) \quad (2.5)
$$

where $Z$ and $N$ are the numbers of protons and neutrons, $Z_\pm$ and $N_\pm$ and the numbers of spin up/down protons and neutrons, $F(Q^2)$ is the nuclear form factor and is $\sim 1$ for small momentum transfers. The $g^p$'s are the vector and axial couplings to protons whereas the $g^n$'s refer to couplings with neutrons. For spin-zero nuclei, the total cross section will be dominated by\cite{11}:
where $\sigma_{\nu A}$ is the neutrino-nucleus cross section, $E_\nu$ is the neutrino energy, $Z$ and $N$ are the number of protons and neutrons in the recoiling nucleus, and $w_p$ and $w_n$ and the weak charges of the proton and neutron. With the weak charge of the neutron roughly equal to 1 and the weak charge of the proton roughly 0, the cross section for coherent scattering is approximately proportional to $N^2$.

The CEvNS process requires that for a medium-size nucleus the neutrino energy be no larger than 50 MeV for coherence, and by kinematics, the largest possible nuclear recoil energy is given by $T_{\text{max}} = \frac{2E^2_\nu}{M+2E_\nu}$. Therefore, for average nuclear masses, the energy of the recoiling nucleus will be $O(10 \text{ keV})$. This is at or below the current limits of detector technologies for large neutrino detectors. This is a key reason why CEvNS had not been measured until 2017. Advanced detector technologies, in part developed for direct dark matter searches where the signal is also a low-energy nuclear recoil, have led to the successes in CEvNS detection.

The pion-decay-at-rest ($\pi$-DAR) neutrino spectrum sits nicely in the required tens of MeV neutrino energies. Additionally, the Spallation Neutron Source is a pulsed source where the sub-1 $\mu$s beam is separated in time from the next pulse by more than 16 ms giving a very favorable duty factor for steady-state background subtraction. The ratio of time coincident with beam and the time not coincident with beam is called the duty factor. In addition, the SNS was designed to be the most intense pulsed neutron source in the world. The only successful CEvNS measurements to date have taken place at the SNS.

CEvNS is particularly interesting as a neutrino interaction channel. The large cross section allows for large rates that are not achievable in neutrino experiments.
with the same scale of detector material. It is the interaction itself that makes
CEvNS more interesting. Except for a small flavor-dependent charge radius effect,
the interaction is not dependent on the flavor of the neutrino and is said to be
“flavor-blind.” Deviations from that would suggest that the interaction is Beyond
the Standard Model (BSM).

Allowing general NSI parameters as in [54, 55], Equations 2.4 and 2.5 become:

\[
G_V = [(g_V^p + 2\epsilon_{ee}^V + \epsilon_{ee}^d)Z + (g_V^n + \epsilon_{ee}^u)]F_{nuc}(Q^2) \tag{2.7}
\]

\[
G_A = [(g_A^p + 2\epsilon_{ee}^u + \epsilon_{ee}^d)(Z_+ - Z_-) + (g_A^n + \epsilon_{ee}^u + 2\epsilon_{ee}^d)(N_+ - N_-)]F_{nuc}(Q^2) \tag{2.8}
\]

These \(\epsilon\)’s are the general vector and axial non-standard interaction (NSI) parameters
for electron neutrino interactions with quarks. The \(G_A\) is small for most nuclei.
The NSI would show up as an increase in cross section from the Standard Model
calculation. Figure 2.4 shows COHERENT constraints on some NSI terms. Here the
muon neutrino cross section is fixed to the Standard Model value and the electron
neutrino cross section floats. The allowed regions for \(\epsilon_{ee}^u\) and \(\epsilon_{ee}^d\) are shown.

The nuclear form factor, \(F_{nuc}(Q^2)\), affects the CEvNS cross section. At \(Q^2 = 0\)
the nuclear form factor is 1. For \(Q \neq 1\), the form factor can be expanded to include
terms in higher orders of \(Q^2\) [56]. The expanded form contains terms dependent on
the neutron density function. Different values for the neutron density function create
distortions in the recoil spectrum from CEvNS. The neutron radius is the root mean
square of the neutron distribution in the nucleus. The difference in rate for the known
uncertainty in neutron radius, which defines the neutron density, can result in small
difference in recoil rates, primarily at large recoil energy. Careful measurements of the
CEvNS recoil spectrum may lead to improved measurements of the neutron radius.
The cesium neutron radius, for example, has a 3% uncertainty. This uncertainty may
be reduced with future precision measurements using CEvNS [60].

Other physics accessible with CEvNS is neutrino magnetic moment. A Standard Model neutrino may have a magnetic moment given by [57]:

$$\mu_\nu = 3 \times 10^{-19} \left( \frac{m_\nu}{1\text{eV}} \right) \mu_B$$

(2.9)

The neutrino mass, $m_\nu$, is less than 1 eV and $\mu_B$ is the Bohr magneton. This tiny magnetic moment is too small for current experiments to measure. However, BSM physics may result in a neutrino magnetic moment that is several orders of magnitude larger [58]. For $\mu_{\nu_\mu} = 10^{-10} \mu_B$, there is substantial enhancement to the CEvNS cross section at low recoil energies relative to the cross section for electron recoils. Low threshold germanium detectors may be a way to target the spectrum at the lowest recoil energies to search for surprisingly large neutrino magnetic moments [37]. The current limit for the magnetic moment of the muon neutrino is $\mu_{\nu_\mu} < 6.8 \times 10^{-10} \mu_B$ [61].
Figure 2.4: Measurements of CEvNS provide handles to test beyond the Standard Model (BSM) physics which are complementary to other kinds of measurements. COHERENT CEvNS measurements already put some constraints on some BSM physics. The left panel shows NSI constraints from the 2017 CEvNS measurement with CsI[Na] and the 2020 CEvNS measurement with CENNS-10. Figure from [3]. Updated results from CsI[Na] give even tighter constraints on NSI parameter space in the right panel. Figure from [52].

A great deal of BSM physics can be probed using CEvNS. In order to do so requires low-threshold detectors to detect the smallest nuclear recoils and very low small backgrounds. The neutrino spectrum needs to be well understood. The first constraints on BSM physics using CEvNS are just the beginning of many more to
come.
Chapter 3

NEUTRONS IN NEUTRINO EXPERIMENTS

Neutrons can play a prominent role in neutrino experiments for a variety of reasons. They are part of the final-state signal in inverse-beta decay experiments. They may be background at a nuclear reactor experiment. They show up in abundance at nuclear reactors and many experiments are done underground to avoid neutrons from cosmic rays. Ultimately, any time neutrons are in abundance around a neutrino experiment, they will need to be characterized in order to fully understand any neutrino signal.

3.1 NEUTRONS IN SCINTILLATOR

Many detectors rely on scintillation for particle detection. The scintillation process involves excitation of the detector material by an incoming particle followed by the deexcitation via the release of light. The scintillating material is transparent to this light which is then collected and read out using a photomultiplier tube (PMT).

The excitation of the detector material is caused by energy transfer from the incident particle. The incident particle may be a muon, a gamma, or even a neutron. The incident particle may or may not deposit all of its energy in the detector. The amount of light released during deexcitation is related to the energy deposition - larger energy depositions will produce more light.

Neutrons can produce scintillation in this way. A neutron can scatter off of atomic nuclei in the scintillator. Organic scintillators are particularly adept at seeing neu-
trons. The incident neutron readily scatters off of the hydrogen nuclei in the plastic and those recoiling nuclei deexcite by emitting light.

Neutrons may thermalize in the scintillator material. A thermal neutron is one that has lost most of its kinetic energy and now has the same temperature of the material that it is in. The thermalization process may happen over several interactions in the material, each of which may produce its own scintillation light. Distinguishing among the various particle types which produce scintillation may be important. Neutron capture may follow thermalization.

3.2 NEUTRON CAPTURE IN NEUTRINO EXPERIMENTS

Neutron capture is a very important process in physics. It is important in nucleosynthesis and stellar evolution. It is how water becomes heavy water. It is the primary driver of reactions in nuclear reactors. Neutron capture has been studied for as long as the neutron has been known. The capture cross sections increase significantly for thermal neutrons compared to fast neutrons.

Neutrons do not survive very long as free particles. For this reason, a free neutron will either capture on a nucleus or decay into a proton, electron, and electron antineutrino. This fact complicates dedicated neutron experiments.

One commonly observed neutron capture mechanism is the thermal neutron capture on hydrogen. The capture cross section for this process is relatively large at a .33 barns\cite{38}. During this process, a characteristic 2.22 MeV gamma is emitted.

\[ ^{1}_{0}n + ^{1}_{1}H^{+} \rightarrow ^{2}_{1}H^{+} + 2.22 \, MeV \]  

(3.1)
This characteristic gamma is oftentimes used to signal the neutron capture on hydrogen in water in experiments. “Neutron tagging” involves identifying a neutron in this manner wherein the gamma(s) from neutron capture is measured.

Another important neutron capture process in neutrino experiments is the capture of thermal neutrons on gadolinium. Gadolinium is particularly interesting because it has the largest thermal neutron capture cross section for stable nuclear isotopes\[39\]. Compare the cross section of 254kb to the 330 mb cross section on water and gadolinium’s advantage becomes clear. This reaction releases a cascade of up to a few gammas totaling nearly 8 MeV in energy.

\[
{\text{\textit{1}}}^0 _n + ^{157}_{\text{\textit{64}}} \text{Gd} \rightarrow ^{158}_{\text{\textit{64}}} \text{Gd} + 7.9 \text{ MeV}
\]  

There are several examples of “gadolinium doping” being used to detect neutrons and there are even neutrino experiments taking advantage of the enormous cross section \[49, 50, 51\]. The neutron produced in inverse beta decay can capture on gadolinium and tag the neutrino interaction. The number of neutron capture processes are too numerous to list, but there are many others of interest. In neutrino experiments, neutron captures can be either part of the signal, such as when neutron tagging is desired, or can be a source of background.

3.3 NEUTRONS AS BACKGROUND IN NEUTRINO EXPERIMENTS

While neutrons can be useful as part of the neutrino signal in some experiments, in others neutrons are a troubling background. Neutrons can be especially problematic as a background when compared to other common sources in neutrino experiments.
When neutrons serve as a primary background, great care is often needed to fully understand those neutrons and results can be limited by the understanding of those neutrons.

Many of the best terrestrial neutrino sources are also very intense neutron sources. Nuclear reactors, for example, are intense neutrino sources but are also intense neutron sources. The Spallation Neutron Source was built as an intense, pulsed neutron source but is also useful as a neutrino source. Neutrons and neutrinos may both produce neutrons following an interaction with atomic nuclei.

Neutrons are especially difficult as background for a few reasons. The first, neutrons, like neutrinos, do not have charge. Particles that can be identified and rejected from analysis are said to be vetoed. When a muon veto is used in an experiment, it is designed to detect muons to reject those particles and their interactions from the experimental data. Charged particles are easier to veto because they interact electromagnetically. Neutron vetoes would be far less reliable.

The second reason neutrons are troublesome as a background is because they can leave signals that mimic neutrino signals. Neutrons will interact with the nucleus of an atom instead of with the electrons. Therefore, nuclear recoils or excitations may be an indication of a neutron interaction. Neutrinos can interact with the nucleus in much the same way. A nucleus that is recoiling due to an interaction with a neutron and a nucleus that is recoiling due to an interaction with a neutrino are indistinguishable from one another.

All of this gets back to the original problem with neutrons as a background, which is that they are often very abundant near intense neutrino sources. Neutrons are hard to identify, their signal can mimic neutrino signals, and there are many of them. The reducibility of neutron backgrounds can be the difference between an experiment that has a measurable result and one that does not.
3.4 NEUTRON-INDUCED NEUTRONS

When neutrons scatter off of atomic nuclei, those nuclei may become excited in the process. One possible path for the deexcitation is for the nucleus to emit gamma rays. In some cases, the nucleus may emit one or more neutrons in addition to gamma rays. If the scatter is energetic enough, in some cases the nucleus may even break into several fragments.

A troublesome path for neutrons as a neutrino background is the case where the nucleus emits one or more neutrons. In this case, the initial neutron in effect multiplies. The multiplicity is related to the number of secondary neutrons that result from the primary neutron. Those neutrons will then be a component of the neutron background spelled out previously. These neutrons can be difficult to manage because many shielding materials used in neutrino experiments are susceptible to this process.

3.5 NEUTRINO-INDUCED NEUTRONS

Similar to secondary neutron-induced neutrons, neutrons can be emitted from nuclei that are excited by neutrinos. Without identifying the source of the primary particle, these two cases may be indistinguishable from one another on an event by event basis. This is another reason why for many neutrino experiments it is critical to manage and/or measure the neutron backgrounds.

Neutrino-induced neutrons (NINs) can be emitted alongside gammas in a nuclear deexcitation. These neutrons can be especially challenging in a neutrino experiment because they are created in shielding materials, near target materials, by the very neutrinos that are being studied. One popular shielding material, lead, is particularly
interesting in regards to NINs. Lead nuclear deexcitations may take the form:

\[
^{208}\text{Pb} + \nu \rightarrow ^{208}\text{Pb}^* + \nu' \rightarrow ^{208-x}\text{Pb} + \nu' + xn + y\gamma
\] (3.3)

\[
^{208}\text{Pb} + \nu_e \rightarrow ^{208}\text{Bi}^* + e^- \rightarrow ^{208-x}\text{Bi} + e^- + xn + y\gamma
\] (3.4)

where \(x\) and \(y\) are the number of neutrons and gammas produced, respectively. In each case, the final state contains one or more neutron(s) in addition to the gammas.

This process can be signal or background depending on the type of neutrino experiment involved. Most low-energy neutrino experiments are exploring neutrino interactions on other target materials and NINs are a potential background source. Other direct measurements of NINs, however, use the secondary neutrons to identify a neutrino source. The Helium and Lead Observatory (HALO) was specifically built to use NINs in lead to detect supernovae\cite{40} and COHERENT has built Neutrino Cubes to measure the NIN cross section on lead and iron. The Neutrino Cubes are discussed in Chapter\ref{chap5}. 

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Chapter 4

COHERENT AT THE SPALLATION NEUTRON SOURCE

The COHERENT Collaboration is made up of nearly 100 collaborators from more than 20 institutions globally[1]. The collaboration was formed in 2013 with the primary objective of measuring Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) for the first time. The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) was identified as a potentially ideal location for a CEvNS measurement and in 2017 the COHERENT Collaboration achieved its goal by measuring CEvNS at the SNS with a cesium iodide detector[2]. COHERENT followed this measurement up with the second measurement of CEvNS, this time with liquid argon (LAr), in 2020[3][4].

4.1 THE SPALLATION NEUTRON SOURCE

The SNS is one of several Department of Energy Office of Science user facilities located at ORNL[5]. Due to the intensity of the neutrons from the SNS, and the accompanying assortment of world-class instruments, state-of-art experiments are carried out here in fields across the sciences[6].
4.1.1 NEUTRINOS AT THE SPALLATION NEUTRON SOURCE

The high-energy collisions between the accelerated protons and the stationary mercury produce spallation neutrons and other nuclear fragments. Additionally, both charged and neutral pions are produced. The $\pi^0$ decay to photons, electron/positron pair(s), or both. The vast majority of the $\pi^-$ will capture on nuclei within the mercury volume. The final pion type, the $\pi^+$ are more abundant and more interesting. The $\pi^+$ loses its momentum in the sea of charges within the mercury and then decays into a $\mu^+$ and $\nu_\mu$. This happens very quickly with the lifetime for the pion decay being less than 1 ns. The $\mu^+$ subsequently decays into $e^+$, $\nu_e$, and $\bar{\nu}_\mu$. The spectra for this collection of neutrinos is commonly referred to as the pion-decay-at-rest ($\pi$-DAR) spectrum. The $\pi$-DAR spectrum is particularly interesting for CEvNS experiments\cite{CEvNS} and can be seen in Figure 4.2. The $\pi$-DAR spectrum and timing are simulated and shown in Figure 4.3. There is little contamination to the spectrum from pions decaying in flight.

Figure 4.1: The Spallation Neutron Source at Oak Ridge National Laboratory\cite{SNS}.
Figure 4.2: The pion-decay-at-rest energy spectrum. Figure from [7].
Figure 4.3: The pion-decay-at-rest energy spectrum from simulation of SNS neutrinos. There is a small contribution to the π-DAR spectrum from pions decaying in flight (top) in addition to muon capture (around 90 MeV) and kaon production (above 200 MeV). The prompt and delayed neutrinos have some separation in time (bottom) relative to the protons on target (POT). Figure from [2].
The π-DAR neutrino spectrum is well understood and easily modeled. It has the added advantage of the neutrinos having nearly ideal energies for CEvNS. Very high-energy neutrinos will probe the individual nucleons in the nucleus resulting in inelastic interactions. In order to probe the entire nucleus coherently, the energy of the neutrino should correspond to a wavelength that is less than 10 fm. This is larger than the size of the nucleus for most isotopes. For the neutrino, this means neutrino energies below around 50 MeV.

The timing of the neutrinos at the SNS is also a critical component for CEvNS. The delayed neutrinos from the muon decay are useful for searching for signal that is not prompt with the beam. Neutrons, for example, may be coincident with the initial $\nu_{\mu}$ population and therefore complicate analysis. The delayed $\nu_e$ and $\bar{\nu}_{\mu}$, however, would not have the same timing characteristics of any neutron background.

Perhaps even more importantly, the pulsed nature of the SNS has several experimental benefits. The timing of the neutrinos relative to the SNS operations is known. Steady-state background subtraction is related to the fraction of time in the in-beam window compared to the out-of-beam window. The duty factor of the SNS allows for a reduction of these backgrounds by a factor of several thousand. The prompt muon neutrinos arrive in Neutrino Alley in a window no wider than 1 $\mu$s. Since the SNS operates at 60 Hz, this means steady-state backgrounds can be reduced by a factor of roughly $6 \times 10^{-4}$ in that window.

Additionally, triggering at the SNS is much easier than at a location such as a nuclear reactor. The fact that neutrinos are expected in tight windows at known intervals, detectors can be triggered on timing signals instead of thresholds, where signals are only slightly above baseline. This gives the detector effectively zero threshold triggering. A trigger is the event used to initiate recording signals. Signals may be low enough in energy to not be discernible from baseline signals, but the signal is
Example waveform from the CsI[Na] detector. The coincident (C) and anticoincident (AC) windows include a pretrace (P) and region of interest (ROI). This signal demonstrates the advantage of triggering on SNS timing signals rather than thresholds. Figure from [43].

**Figure 4.4:** d there. In contrast, at a nuclear reactor, neutrino arrival times are not known. Triggering must be done on signals instead of timing in this case. Background signals then become problematic because of excessive triggering on low-energy backgrounds. The waveform in Figure 4.4 is from the CsI[Na] data used to make the first CEvNS measurement. This signal was triggered on SNS timing and not actual signal above threshold.

The timing characteristics of the SNS and the $\pi$-DAR neutrinos make CEvNS measurements achievable. However, there are still several challenges. Perhaps the biggest challenge, and the primary reason that attempts at measuring CEvNS were unsuccessful until recently, is the energy of the signal. A coherently-scattered neutrino
produces a recoiling nucleus. The tens of MeV neutrinos have energy that is tiny compared to the mass of the recoiling nuclei. For that reason, the nuclear recoils are very low energy. Neutrinos with energies in the tens of MeV will produce nuclear recoils in the few tens of keV for most atomic masses. Figure 4.5 shows the recoil spectra for a few different elements via CEvNS from \( \pi \)-DAR neutrinos. Only recently have detector technologies reached threshold capabilities for sufficient counts above threshold for these recoil spectra.

### 4.2 COHERENT DETECTORS AT THE SPALATION NEUTRON SOURCE

The primary objective for COHERENT is to measure the Coherent Elastic Neutrino-Nucleus Scattering cross section on several nuclei in order to map out the \( N^2 \) dependence. To that end, those nuclei should be spread out enough to map a wide area of the periodic table rather than a few nuclei with similar \( N^2 \). Additionally, there is a great deal of “beyond the Standard Model” (BSM) physics that can be explored with certain nuclear configurations/isotopes\(^{37}\).
Figure 4.5: Expected recoil spectra from pion-decay-at-rest neutrinos for COHERENT target nuclei at the SNS. Figure from [52]. The recoil energies are in units of keVr, which is the energy in keV of nuclear recoils. Electronic recoils are measured in electron equivalent energies, keVee.
COHERENT has developed a suite of detectors to measure CEvNS, to monitor backgrounds, and to search for new physics. Some detectors have collected data for several years whereas others are coming on line or are in development. By measuring CEvNS with more than one detector, systematic uncertainties can be constrained and backgrounds can be better understood.

4.2.1 NEUTRONS AT THE SPALLATION NEUTRON SOURCE

As the name implies, the SNS relies on the spallation process for neutron production. This process starts with a beam of $\sim 1$ GeV protons which are accelerated into a stationary mercury target. The energetic proton-mercury collisions break apart the...
mercury nuclei wherein neutrons, in addition to other fragments, spall off. For every neutron-mercury collision, there are 20-30 of these spallation neutrons produced. These spallation neutrons are then shielded and moderated so that they can be directed down a number of beam lines. It is there, at the end of the beam lines, where the sophisticated neutron-scattering experiments take place.

The SNS takes advantage of radio-frequency technology to accelerate the protons to roughly 90% of the speed of light in the linear accelerator. These protons are then added to another bunch of protons in the accumulator ring. When more than 1000 turns have been added, the protons are kicked from the ring and directed toward the mercury target where the spallation process takes place.

In order to perform the desired neutron-scattering experiments at the end of the beam lines, these spallation neutrons need to be bunched in time. This is achieved during the accumulation phase in the accumulator ring where protons are added to the bunch. These protons are then delivered to the mercury target at 60 Hz in bunches smaller than 1 \( \mu \text{s} \).
Figure 4.7: The average beam pulse shape in time. This average was taken over an extended period of time, but there is very little variance in shape among individual pulses. From S. Hedges.

These neutrons are beam-related neutrons. There is a timing component to those neutrons which, when selected for, can enhance the signal to noise. This is one of the primary advantages of the SNS is that neutrons come in pulses. When the coincident window is very small compared to the anticoincident window, steady-state backgrounds are more easily subtracted.

There are steady-state neutrons at the SNS. In some locations at the SNS, steady-state neutrons from the SNS target may be an issue. Other locations are sufficiently far enough away from the target, with enough concrete shielding the target, that these steady states are negligible. Cosmic muons, however, are a source of steady-state neutrons throughout the SNS. The muons interact in the concrete and produce neutrons near detectors. Again, however, the pulsed nature of the SNS allows for significant reduction of these neutrons from beam studies.
4.2.2 NEUTRONS AS A BACKGROUND IN COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

Any attempt at making a CEvNS measurement will require careful control of backgrounds. Reactor-based experiments, where neutrino fluxes can be very large, must contend with the large number of neutrons associated with the fission processes. This is because neutrons, like neutrinos, will interact with detector material nuclei via a momentum exchange resulting in a recoiling nucleus. Likewise, at a spallation neutron source, there are going to be neutron backgrounds to contend with. For this reason, it is important to select a site that minimizes signal contamination from neutrons without being too far away to measure a signal.

High-energy neutrons can provide additional challenges because of their ability to multiply in shielding materials. Measuring CEvNS requires very sensitive detectors and these are often shielded from environmental backgrounds like muons and gamma rays. These shielding structures, particularly those used to shield gammas, are often made from high-Z materials. High-energy neutrons can multiply by interacting in the high-Z material and kicking out additional neutrons. This is particularly problematic because this shielding material is often very close to the sensitive detector volume. Instead of one high-energy neutron, there can now be several lower-energy ones if the initial neutron energy is above the multiplicity threshold.

An additional source of neutron background to consider in CEvNS measurements comes from Neutrino-Induced Neutrons (NINs). This process starts when a neutrino inelastically interacts, generally in a high-Z material, by exciting the nucleus. That nucleus then de-excites by emitting one or more neutrons and/or gammas. Again,
because this high-Z material is near the detector, those de-excitation neutrons can reach the detector and leave behind a signal that mimics CEvNS.

4.3 QUENCHING FACTORS

Quenching factors represent one of the more challenging aspects when dealing with nuclear recoils. Nuclear recoils and electronic recoils may have different characteristics when they appear in data. Pulse-shape discrimination (PSD) relies on the fact that nuclear and electronic recoils sometimes have a different timing profile, depending on the material. In plastic, for example, recoils are usually measured by adding up light produced during the interaction. In plastic, light from electronic recoils tends to be produced quickly when compared to light from nuclear recoils. Therefore, by comparing fraction of “fast” light to the fraction of “slow” light, nuclear and electronic recoil populations may separate out. The material used can have characteristics that affect the timing in different ways, but PSD can be useful for background subtraction.

Similarly, the amount of light produced during interactions may differ. There will be less light produced in a low energy electronic recoil than in a high energy one of equal energy. Likewise for nuclear recoil events. When comparing electronic recoils to nuclear recoils of the same energy, the quenching factor is what matters. There will generally be less light produced in a nuclear recoil event than in an electronic recoil event.

The fraction of light produced during nuclear recoil events versus electronic recoil events is called the quenching factor. This number is generally between zero and one. These nuclear recoils can be from either neutron scatters or neutrino scatters, though, experimentally, neutron scatters are easier to measure. The quenching factor is very important when any recoil spectrum is analyzed. Quenching factor measurements for
CsI[Na] and liquid argon can be seen in Figures 4.8 and 4.9 respectively.

**Figure 4.8**: The CsI[Na] quenching factor measurements that were used for the updated COHERENT CEvNS measurements. Figure from [52].
Figure 4.9: The LAr quenching factor measurements that were used for the COHERENT CEvNS measurements. Figure from [4].

4.4 SITE SELECTION AT THE SPALLATION NEUTRON SOURCE

The intense, pulsed, $\pi$-DAR neutrinos at the SNS made it a leading candidate for COHERENT to attempt a first measurement of CEvNS. The primary problem was finding a site where the intense neutron source would not overwhelm the neutrino signal. In 2014, the Neutron Scatter Camera (NSC) was deployed around the SNS to try to find a location where neutron rates were low enough that a CEvNS experiment might be possible[12]. The NSC uses a series of scintillator cells and timing to infer energy and direction information about the neutrons. Results from those measurements can be seen in Figure 4.10
A basement-level access hallway was discovered as having a significant reduction in neutron rates relative to other locations on the SNS instrument floor. This low rate was confirmed later with SciBath, a portable neutron detector designed to measure neutrons near intense neutrino sources [62]. This hallway is now informally referred to as “Neutrino Alley” and all of COHERENT’s ongoing measurements are being performed there. The hallway provides significant shielding from the SNS neutrons and additionally modest shielding against cosmic backgrounds with an 8 meter water equivalent overburden. However, there is a hot off-gas pipe which significantly increases low energy gamma backgrounds. This pipe, located less than a few meters away from the detector directly across the hall, is used to remove spallation fragments from the SNS target and is a source of high rates of 511 keV gammas. For this reason, all of the CEvNS detectors are shielded with lead to block this low-energy background.
Chapter 5

COHERENT DETECTORS AND ONGOING MEASUREMENTS AT THE SPALLATION NEUTRON SOURCE

Figure 5.1: Locations of COHERENT detectors in Neutrino Alley.

The first measurement of CEvNS was performed with a cesium iodide detector that took data from 2015-2019. The updated measurement coming in 2021 is with the entire data set and represents 2.2 times the data from the 2017 result. The next
CEvNS measurement, on liquid argon (LAr) was done with CENNS-10. That detector has been in Neutrino Alley since 2017. In addition to those detectors, there are ongoing efforts to measure CEvNS with sodium iodide, and soon germanium. There is an effort to measure NINs with the Pb Nube and Fe Nube which are palletized “Neutrino Cubes” that have been collecting data since 2016 and 2017 respectively.

In addition to measuring NIN backgrounds, there is an effort to monitor beam-related neutrons (BRN). These neutrons are the ones that can interact in a detector, or in surrounding shielding material, and could cause background signals in CEvNS measurements. A measurement of the neutron rate in the hallway as a function of time could be used to better model those backgrounds for all of the CEvNS detectors at the SNS. For this reason, the Multiplicity And Recoil Spectrometer (MARS) was deployed to the SNS in 2017. The details of its operation and work toward measuring a neutron spectrum are the focus of this work.

**Table 5.1**: The CEvNS detectors at the SNS. The CsI[Na] detector was used to make the first CEvNS measurement in 2017. The detector has been decommissioned. The LAr detector, CENNS-10, was used to make the second CEvNS measurement. The 185 kg NaI[Tl] detector is a prototype for a ton-scale upgrade planned for the near future. The Ge detector will be commissioned in 2021.

<table>
<thead>
<tr>
<th>Detector target material</th>
<th>Mass (kg)</th>
<th>Distance to Target (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI[Na]</td>
<td>14.6</td>
<td>19.3</td>
</tr>
<tr>
<td>LAr</td>
<td>24</td>
<td>27.5</td>
</tr>
<tr>
<td>NaI[Tl]</td>
<td>185</td>
<td>28</td>
</tr>
<tr>
<td>Ge</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

### 5.1 THE CSI DETECTOR

The first successful measurement of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) on any nuclei was performed by COHERENT using a sodium-doped ce-
sium iodide detector[2]. The 14.6 kg crystal of CsI[Na] is the primary neutrino target material and is shielded with lead and water to reduce environmental backgrounds.

Figure 5.2: d

The CsI[Na] was chosen for economic and performance reasons. These crystals are relatively inexpensive and easily obtained. They are also low background and high light-yield and therefore have low thresholds. Cesium and iodine are also very close to one another in the number of neutrons and thus make analysis of the $N^2$
dependence more simple. The detector was located in Neutrino Alley in the location with the shortest baseline to the SNS target to maximize neutrino flux.

The CsI[Na] detector was positioned in a location known to have very low neutron rates. The neutrons from the SNS target are expected to be more forward scattered relative to proton beam. The CsI[Na] location was closer to 90 degrees relative to the beam as seen in Figure 5.1. In order to assess the magnitude on beam neutrons and neutrino-induced neutrons (NINs) in the shielding, an EJ-301 liquid scintillator cell was placed inside the shielding to measure these backgrounds. Figure 5.3 shows that the neutron background has a very small delayed component. Nearly all of the neutrons arrive in the first 1000 ns after the protons on target.
Once the neutron characterization measurement was completed, the EJ-301 cell was replaced by the CsI[Na] detector. After nearly two years of data-taking at the SNS, COHERENT compared beam-on to beam-off data with CsI[Na] to look for the CEvNS signal. Data analysis consisted of comparing windows in time both before and after the SNS timing signals. In this way, events such as afterglow from a previous energy deposition could be removed from the data set.

For the first analysis in 2017, a two-dimensional analysis of energy and time for beam-on and beam-off periods shows a clear excess for the beam-on periods. The excess rejects the null hypothesis of no CEvNS at a level of 6.7σ. The best-fit CEvNS event count is 134 ± 22 which is within 1 σ of the Standard Model prediction of 173.
The beam related neutron backgrounds are nearly fully contained in a single, prompt time bin and are a fraction of the CEvNS signal in that bin. The NIN contribution is even smaller. This is a clear win for the SNS as a CEvNS location.

The CsI[Na] received another two years of exposure after the initial result. This detector was decommissioned in 2019 and that valuable space in Neutrino Alley will be the site of future measurements on other nuclei.

**Figure 5.4:** The first measurement of CEvNS was reported using CsI[Na] by COHERENT in 2017. The excesses in detected photoelectrons (top) and time (bottom) can be seen when comparing beam on and beam off. The contributions to signal from each neutrino flavor and from beam neutrons are seen.

COHERENT has worked on improving quenching factor measurements on CsI[Na] as this represents the primary uncertainty in reported CEvNS results. The quenching factor is important because calibrations are done with gamma sources which scatter electronically whereas CEvNS is a nuclear recoil process. In order to compare the two types of recoils to one another, a good measurement of the quenching factor over
the range of energies in question is needed. These highly sensitive measurements help improve on energy reconstruction and help narrow the uncertainties in energy for the nuclear recoils. These measurements can be done after the neutrino data has been collected and previous data can be reanalyzed with improved quenching factor measurements. The measurements of the CsI[Na] quenching factor can be seen in Figure 4.8.

A two-dimensional analysis of the full data set in energy and time was performed. The new result rejects the null hypothesis of no CEvNS at a level of 11.6σ. There were 320 ± 20 CEvNS events compared to the Standard Model prediction of 333 ± 11.

The beam related neutron backgrounds are only about 7% of the CEvNS signal. The uncertainties on the total rate normalization for beam neutrons and NINs are 0.9% and 0.5%, respectively. This still represents a subdominant uncertainty in the CEvNS calculation. With improved quenching factors, the primary uncertainties are now statistical. The dominant systematic uncertainties for both results are shown in Table 5.2. The results from the two-dimensional analysis can be seen in Figure 5.5.

Table 5.2: The largest contributors to systematic uncertainties for the two CsI[Na] CEvNS measurements. The leading systematic uncertainty in the new analysis is from the neutrino flux. [52].

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Uncertainty (2017) (%)</th>
<th>Uncertainty (2021) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino flux</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Quenching factor</td>
<td>25</td>
<td>3.9</td>
</tr>
<tr>
<td>Efficiency</td>
<td>5.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Light yield</td>
<td>5.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Figure 5.5: An updated CsI[Na] result from 2021. This represents more than twice the data from the 2017 result. The excess in detected photoelectrons (PE, left) and in time (right) are shown. The contributions to the signal can be seen for each of the three neutrino flavors. The beam neutrons and NINs can be seen contained in the first 1000 ns. This result is an 11.6σ rejection of the no-CEvNS hypothesis. Figure from [52].

5.2 THE CENNS-10 DETECTOR

The second successful measurement of CEvNS was also performed by the COHERENT Collaboration[3, 4]. This time the measurement was performed using a 24 kg single-phase liquid argon (LAr) detector CENNS-10 that was repurposed to measure CEvNS. This measurement represents a big step toward measuring the $N^2$ dependence of the CEvNS cross section because argon is a much lighter target nucleus than cesium and iodine. Because of its lighter nucleus, argon recoils will be of higher energy than those on cesium iodide. Like the CsI[Na] detector before it, CENNS-10 has a high light yield which allows for low threshold measurements. Several upgrades and calibrations were performed throughout its time in Neutrino Alley to improve and verify the very low threshold capabilities of CENNS-10. This detector has collected data in Neutrino Alley since 2017 and because of footprint considerations is on a longer baseline than the CsI[Na] detector. CENNS-10 is too large to fit anywhere
in Neutrino Alley except in the wider alcove near the end of the hallway.

Figure 5.6: Schematic drawing of the CENNS-10 detector. Figure from [45].
Figure 5.7: The CENNS-10 detector is a 24 kg liquid argon detector used to make the second CEvNS measurement by COHERENT.

CENNS-10 is located in the widest part of Neutrino Alley because it is the largest COHERENT detector in operation. This can be seen in Figure 5.1. This location unfortunately has a significantly higher neutron rate than the CsI[Na] location has. SciBath, which will be discussed later, was placed in the CENNS-10 location before the deployment of CENNS-10 in order to measure the neutron spectrum in that location. Additionally, CENNS-10 was operated without its water shielding to measure the beam neutron flux in that location. NINs, again, are a tiny background in the overall CEvNS analysis.
Figure 5.8: The beam neutron flux measured by SciBath in the CENNS-10 location. This is the input for the beam neutron flux for CENNS-10 analysis. Figure from [47].

CENNS-10, like the CsI[Na] detector, takes advantage of triggering on the SNS timing signal rather than on signal above threshold. Waveforms for the two photomultiplier tubes (PMTs) are recorded for each trigger. CENNS-10 is capable of pulse-shape discrimination (PSD). Depending on what type of interaction occurs on the argon, nuclear recoil or electronic recoil, the amount of light produced quickly or slowly will differ. For nuclear recoils in argon, more of the light is produced quickly. For electronic recoils, less light is produced quickly [47].

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The quantity used for PSD is referred to as $F_{90}$. This is the fraction of the total light that is collected in the first 90 ns of the waveform. Nuclear recoils have $F_{90}$ around 0.7 and electronic recoils have $F_{90}$ closer to 0.3. CEvNS events are nuclear recoils, so an $F_{90}$ cut helps reduce backgrounds.

In addition to triggering on SNS timing signal, CENNS-10 is triggered between SNS signals in order to assess steady-state backgrounds. A maximum likelihood fit was performed for time, reconstructed energy, and $F_{90}$ for events in the region of interest. The results of these fits, with steady-state backgrounds subtracted, are shown in Figure 5.9. The green bands represent 1σ errors.

![Figure 5.9](image)

**Figure 5.9:** The result of maximum likelihood PDF fits. The steady-state backgrounds have been subtracted for ease of viewing of the CEvNS and beam-related neutrons (BRNs) contributions. The time, reconstructed energy, and $F_{90}$ are shown. Figure from [3].

The CENNS-10 data analysis was performed simultaneously by two independent groups within COHERENT. Both analyses reject the no-CEvNS hypothesis at a level greater than 3.0σ. The number of measured CEvNS events agrees with the Standard Model prediction to within 1σ for both analyses.

Unlike for CsI[Na], the beam neutrons are a significant component of the total counts in the CEvNS sample. For the updated CsI[Na] results only 17 beam neutrons were in the data sample compared to 306 CEvNS events and this represents a roughly
1% uncertainty on the CEvNS measurement. For CENNS-10 there were 553 beam
neutrons compared to 153 CEvNS events. The systematic uncertainty on the beam
neutrons was 6.7%. The total systematic uncertainty for the likelihood fits was 8.5%,
so tighter constraints on the beam neutrons can have a significant effect on reducing
the uncertainty for CENNS-10. Improvements on measuring beam neutrons in this
location will help constrain that component further and improve results. The largest
contributors to systematic uncertainties are shown in Table 5.3.

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino flux</td>
<td>10</td>
</tr>
<tr>
<td>Likelihood fit shape</td>
<td>8.5</td>
</tr>
<tr>
<td>Prompt light fraction</td>
<td>7.8</td>
</tr>
<tr>
<td>Detector Model</td>
<td>2.2</td>
</tr>
<tr>
<td>Form factor</td>
<td>2.0</td>
</tr>
</tbody>
</table>

This result simultaneously validates the previous successful measurement and
motivates further tests on other nuclei. Future measurements with LAr are being
explored with a larger detector volume in order to increase statistics.

A much larger version of CENNS-10, CENNS-750, is currently in development.
Additional measurements of the beam neutrons are planned for the location as well.
MARS, which will be a focal point of later chapters, will be moved to the CENNS-10
location as soon as data-taking stops for that detector.
5.3 OTHER COHERENT CEVNS DETECTORS

COHERENT is also actively pursuing measurements of CEvNS on additional nuclei. A prototype thallium-doped sodium iodide detector system is currently collecting data in Neutrino Alley. This prototype serves as a test for a ton-scale experiment using the NaI[Tl] crystals. This would be the largest (by mass) detector by far that COHERENT has used and would represent the first detector capable of simultaneously measuring the charged-current and CEvNS interactions. These crystals are not as low threshold as the CsI[Na] and CENNS-10 detectors but make up for that deficiency in mass.

Germanium has long been on the list of desirable target nuclei. Interest in development of low threshold detectors is not limited to neutrino physicists. Dark matter searches require very sensitive, low background, low threshold detectors as well. A great deal of research and development has gone into improving germanium detectors for low energy event searches.

COHERENT has begun purchasing germanium crystals for a CEvNS measurement on that target and a working detector should be in place very soon. Germanium, which has good energy resolution and low backgrounds, represents an ability to do the most sensitive CEvNS measurement to date.

5.3.1 OTHER DETECTORS

In addition to measuring CEvNS, there are other measurements which can and/or should be done in conjunction. Background and beam monitoring are important things to keep track of. Complementary measurements of other neutrino interactions are also possible and may provide additional useful information. The COHERENT detectors, and their exposures to SNS beam, can be seen in Figure 5.10.
The NaI[Tl] detector will measure not only CEvNS, but the charged-current interactions as well. This is possible with a large, segmented detector because the charged-current events may begin within inner cells of the detector. By using the outer layers as an active veto, leptons which originate from neutrinos interacting in the NaI can be separated from those which originate outside the detector.

SciBath is a 821 L liquid scintillator detector that was built to measure neutrons in underground locations[41]. SciBath collected data for a few months in 2015 in the location of the CENNS-10 detector in order to measure neutron rates for background characterization. SciBath was removed once CENNS-10 was deployed but its measurement is used in the CENNS-10 analysis for beam-related neutrons.

The Multiplicity And Recoil Spectrometer (MARS) was also built to measure neutrons in underground experimental facilities. MARS utilizes plastic scintillation and neutron capture on gadolinium to measure neutron rates and energies. It was deployed in 2017 and has measured neutrons in two separate locations in the Neutrino Alley. MARS is being used to look at neutron rates over long periods as a monitor of neutron backgrounds. Its characterization is the subject of this thesis.

The Neutrino Cubes, or nubes, are used to measure NINs. NINs have never been measured directly. Unlike CEvNS, the NIN process is not as well constrained by the Standard Model and is very interesting for nuclear physics. There are two Neutrino Cubes - the lead nube and the iron nube. They are currently collecting neutrino data and results are expected out soon.

One additional uncertainly in the COHERENT CEvNS measurements is the neutrino flux from the SNS. In order to better assess that, a heavy water detector has been proposed to be built near Neutrino Alley. This detector could simultaneously measure the neutrino flux by looking for interactions with well-known cross sections (the neutrino-deuterium charged-current interaction) while measuring cross sections.
that are not well known (the neutrino-oxygen charged-current interaction).

Figure 5.10: All COHERENT detectors and their exposure to protons-on-target. CEvNS detectors are drawn with thicker lines. COHERENT has been in Neutrino Alley long enough that more than 1 mol of protons has been delivered to the target at the SNS. Figure from E. Conley.

5.4 WHY NEUTRONS MATTER

For all of the CEvNS detectors, neutrons from the SNS beam contribute to the CEvNS signal. This is particularly true in the prompt timing window. Beam neutrons can interact in the detector itself and produce a recoiling nucleus that looks like a CEvNS event. These neutrons, like the neutrinos, are coincident with the beam and are therefore not eliminated with timing cuts. Incredibly precise timing would be needed to separate the neutron signal from the neutrino signal completely.

Neutrons may also interact in nearby material such as concrete or detector shielding to produce secondary neutrons. These neutrons, like their parent particle, can interact in the detector and mimic CEvNS signals. These beam-related neutrons are the primary background in the CEvNS detectors which is not a steady-state background.

A dedicated neutron-characterization campaign could address outstanding uncer-
tainties around beam neutrons. Detailed measurements of the rate and spectrum throughout Neutrino Alley would serve as inputs to simulation and analysis for all detectors. The goal of this campaign would be to ensure that systematic uncertainties related to beam neutrons are a subdominant component of the total uncertainty in all detectors.
Chapter 6

THE MULTIPLICITY AND RECOIL SPECTROMETER

The Multiplicity And Recoil Spectrometer (MARS) was built at Sandia National Laboratory to measure high-energy neutrons in above and below ground environments\[13\]. It was intended to measure low fluxes of these high-energy neutrons efficiently in order to shorten the needed exposure times for a measurement. By making quick measurements, and being easily transportable, MARS could be used to make several measurements in different locations. MARS has been used at the Kimballton Underground Research Facility (KURF)\[14\] and the Spallation Neutron Source (SNS) to measure neutron fluxes that are backgrounds for other particle physics experiments. The COHERENT collaborators at Sandia National Laboratory deployed MARS to the SNS in 2017.

MARS was designed as a pair of detector modules that were set on either side of a lead volume as shown in Figure 6.1. The original multiplicity technique for measuring neutron energies relied on a high-energy neutron multiplying in the lead volume. Neutrons can inelastically scatter off of neutron-rich lead nuclei and secondary neutrons result from the deexcitation of the lead. Those neutrons were then detected in either of the two sensitive modules. The number of secondary neutrons is a function of the primary neutron energy, and so counting the number of secondaries gives one a measure of primary energy. Background suppression was achieved through requiring the number of secondaries counted to be above a minimum number.

Plastic scintillator is a detector material for many types of particle interactions.
Muons, for instance, deposit a great deal of energy in plastic scintillator as they pass through the material. The muon’s charge means it interacts electromagnetically with the plastic constituent nuclei. Neutrons, unlike the muons, are neutral in charge and therefore do not interact strongly with the plastic. They will, however, scatter off of nuclei and may even capture on the abundant hydrogen. The recoil technique for neutron detection in MARS relies on the recoiling nuclei from neutron scatters.

For both the recoil and multiplicity techniques for neutron detection, MARS relies on neutron capture on gadolinium to select for neutron events. Energy depositions in MARS can come from a number of sources, but neutrons which capture on the gadolinium then have a corresponding event with roughly 8 MeV of energy. By selecting events with a coincident capture event, neutron interactions in MARS can be preferentially selected.
Figure 6.1: MARS was designed to take advantage of the multiplicity of neutrons in lead to measure high-energy neutron fluxes both above and below ground. In Neutrino Alley, only one of these two modules is used. Figure taken from [13].

6.1 HARDWARE, ELECTRONICS, AND PROCESSING

The original design of MARS involved the two separate modules and the volume of lead for neutron multiplicity. In Neutrino Alley at the SNS, the footprint of the original MARS design would not fit in the hallway. Therefore MARS, in its configuration in Neutrino Alley, is only one of the original modules and does not include the lead. Because of this, in Neutrino Alley all neutrons will be detected via the recoil technique instead of both recoil and multiplicity.

A module in MARS (from here forward referred to simply as MARS) is made up
of 12 sheets of BC-408 scintillating plastic [15], each of which is 100 cm × 75 cm and 2 cm thick. Between each of the layers is a Mylar sheet which has been painted with gadolinium loaded paint. The 12 sheets and Mylar layers result in a 100 cm × 75 cm × 25 cm detector volume. The two 100 cm × 25 cm faces are coupled to 10 cm thick light guides, and each light guide is coupled to eight 5-inch photomultiplier tubes (PMTs) [16] as seen in Figure 6.2. In previous applications of MARS, the modules were oriented such that the normal to the large surface was vertical - in Neutrino Alley it is horizontal. This is due to the fact that in those previous applications, the neutrons were cosmic in origin but at the SNS they are coming from the SNS target.

![Figure 6.2: MARS as positioned in Neutrino Alley. Each side consists of 8 PMTs connected to a light guide.](image)

Each of the 16 PMTs is supplied with high voltage and is connected to one of
two Struck SIS3316 digitizers. The SIS3316 is a 14 bit, 250 megasample digitizer card[17]. In addition to the 16 PMT channels, there are two channels which read out timing signals from the SNS. These 18 channels make up the MARS data acquisition (DAQ).

These two signals, “Event 39” and “Event 61,” are 2.5 V Transistor-Transistor Logic (TTL) signals that are generally 60 Hz. This is due to the fact that the SNS operates at 60 Hz. The Event 39 signal is used for timing and the Event 61 communicates whether or not a given SNS cycle involved protons-on-target (POT). The Event 39 signal operates at 60 Hz whether on not the SNS is delivering POT. The Event 61 would be present when there is POT, and missing when not. All windows around the SNS “beam” will be relative to the Event 39 signal. Beam on would be events where both Event 39 and Event 61 had signal.

MARS is triggered by Event 39, Event 61, or a collection of PMTs. By triggering on Events 39 and 61, SNS timing information is integrated into the data stream. Particle interactions in MARS are set to trigger the DAQ as well. To minimize triggering on low energy noise, the MARS DAQ is set up so that four groups of 4 PMT channels are group triggered. When a trigger threshold is exceeded by the group, the DAQ will trigger and record on all channels.

For a trigger on Event 39 or Event 61, only timestamps and channel identification are recorded. For a group trigger, timestamp, channel number, and accumulator values are recorded. The SIS3316 enables recording of up to 8 accumulator values per channel. The accumulators are integrated values from a user-controlled range of the waveform. This allows for a significant reduction in amount of data that is written out. For MARS data collection in Neutrino Alley, the accumulator ranges are set according to Table 6.1.
Table 6.1: The range in time for the accumulators for the MARS DAQ. The times are from the trigger onset. For signals that trigger the DAQ, the entirety of the signal is contained in the first accumulator.

<table>
<thead>
<tr>
<th>Accumulator Number</th>
<th>Start Time (sample)</th>
<th>Length (samples)</th>
<th>Time Window (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>25</td>
<td>0-100</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>25</td>
<td>100-200</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>25</td>
<td>200-300</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>25</td>
<td>300-400</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>25</td>
<td>400-500</td>
</tr>
<tr>
<td>6</td>
<td>125</td>
<td>25</td>
<td>500-600</td>
</tr>
</tbody>
</table>

The plastic scintillator in MARS is fast (∼1 ns rise and decay times) and the entirety of signals that cause a trigger should be contained by the first accumulator. The other 5 recorded accumulators are averaged for a baseline calculation. The light detected during an interaction is calculated by subtracting this baseline from the first accumulator and gives a value in Analog-to-Digital Converter (ADC) units. This light yield is related to the energy deposited during the interaction.

These events are written out as raw binary data. These data are processed to reduce file size and prepare the data for analysis. For Events 39 and 61, only the time of the trigger is important. Each PMT trigger in MARS represents an energy deposition above threshold. The energy deposition may be a result of triggering on noise, background, neutron recoil, neutron capture, or any number of things. The light yield and timing information are important. The first layer of processing involves processing raw events.

Each raw event represents a PMT trigger in MARS. Each of the 16 channels is added together to get the total light collection for the event. This value is related to the energy of the event.
Figure 6.3: The capture-gating method relies on identifying two signal separated in time. The first signal is scintillation light from the neutron down-scattering in the plastic. The second signal is from the neutron capture on gadolinium.

In order to identify neutrons in MARS using the recoil technique, pairs of triggers are necessary. The first trigger would be scintillation light due to the neutron scattering in the detector and the second trigger would be the gadolinium capture. For this reason, the second step in processing MARS data involves making pairs of triggers. For each raw event, a window that is 200 $\mu$s wide is opened. Each subsequent trigger in that window forms a pair with the initial trigger.
Figure 6.4: Pictorial representation of PMT triggers in the data stream. All pairs of triggers are formed and relevant information such as energy and timing are recorded. In this example, there are 6 pairs: the first trigger with the second trigger, the first trigger with the third trigger, the first trigger with the fourth trigger, the second trigger with the third trigger, the second trigger with the fourth trigger, and the third trigger with the fourth trigger. Their timing is recorded relative to the last Event 39. Neutron events are identified according to their energy and timing characteristics.

For example, in Figure 6.4 there are 4 PMT triggers in the data stream. The first trigger would appear in 3 pairs - the first trigger with the second, the first with the third, and the first with the fourth. To avoid repeating pairs, the second trigger would be paired with the third and fourth triggers. Finally, the third and fourth triggers would make the final pair.

For each pair, the relevant data are written out to the final processed data file. The energy, represented by the subtraction of accumulator sum values described previously, is recorded. These two values are referred to as “E1” which is the energy of the first trigger in a pair and “E2” which is the energy of the second trigger. The time since the previous Event 39 in the data stream is recorded. This variable, referred to simply as ‘t,’ is the time to the first trigger in the pair. Likewise, the time since the most recent Event 61 is recorded. This is only used to identify pairs where a
neutron might be expected or not since it is only used to identify beam on versus beam off. And lastly, the time between the two triggers in the pair is recorded as ‘dt.’

6.2 THE CAPTURE-GATING METHOD FOR NEUTRONS

A fast neutron incident on the face of MARS will interact in the plastic scintillator producing light proportional to the kinetic energy of the neutron. This takes place over several interactions as the neutron down-scatters and these interactions occur in rapid succession such that most of the energy is produced within the time contained by the first accumulator. So the total light, and thus total energy, of the down-scatter process will be contained in a single trigger in the detector. The resulting thermal neutron can scatter many times in the plastic with negligible energy deposited. These low energy scatters can occur many times in the plastic and can take place over many microseconds.

The gadolinium layers in MARS allow for detection of thermal neutrons via the capture reaction on gadolinium. This reaction releases $\sim 8$ MeV total energy in up to 5 gammas. Since the gadolinium layers are very thin, the light from this reaction travels in the plastic scintillator, reaches the light guides, and is detected by the PMTs. The capture time for the thermal neutrons has been measured in several different ways and all values agree with one another. This capture time is roughly 25 $\mu$s. The vast majority of thermal neutrons capture on the gadolinium as opposed to capturing on hydrogen because the capture cross section on gadolinium is so large.

Neutron detection with MARS takes advantage of the capture-gating method. Since the characteristic signature for a neutron is a pair of energy depositions sepa-
rated by the neutron capture time, and the energy of the capture event is relatively large and only depends on the neutron capture itself, therefore neutrons can be preferentially separated from backgrounds when looking at pairs of triggers in MARS. By forming all pairs of triggers within a wide time window there will be pairs of triggers associated with a neutron and pairs associated with random backgrounds. The differences show up in the energy spectrum of the second trigger in the pair, labelled “E2” in analysis, and the time between the triggers, labeled “dt.”

By plotting the dt variable for all pairs, the background pairs show up as a flat distribution. Random coincidences are flat in time when all pairs of events are made. However, the signal pairs have a time constant due to the capture time of thermal neutrons. The time between incident neutron signal and the capture signal is not random and therefore will have a time component when making all pairs. The E2 variable will also have a characteristic range associated with the neutron capture energy. With any neutron population in MARS, these two variables are the primary handles for separating neutrons from background. When looking at SNS beam neutrons, or other pulsed, time-tagged neutrons, there may be timing information on the first trigger that helps identify neutron pairs as well.

One disadvantage of using the capture-gate method is the reliance on both events to trigger the DAQ. If an incident neutron does not deposit enough energy to trigger the DAQ, or the thermalized neutron escapes MARS before being captured, this method will miss that neutron. Low energy trigger efficiency and capture efficiency must be measured to account for this.
6.3 DATA COLLECTION AT THE SPALLATION NEUTRON SOURCE

MARS was deployed to the SNS in September 2017. It has collected data there nearly continuously since that time. From 2017 until January 2019 MARS was located a few meters from the location of the CsI[Na] detector used to make the first CEvNS measurement. There was sufficient exposure in that location to make a flux measurement so MARS was moved to a new location. This location is the site designated for the future germanium array. In this work, only data from the original location will be considered.

In addition to operating nearly continuously to measure SNS beam neutrons, several characterization measurements were taken. Those measurements will be detailed in later chapters. Unless otherwise stated, all threshold, trigger, and timing settings were kept constant for the characterization measurements so that the results can be confidently compared to SNS beam data.

Neutrons at the SNS will generally come from one of two sources - environmental neutrons from room material or the SNS target. Room neutrons can come from cosmic muons interacting in concrete around Neutrino Alley for example. These room neutrons will be random in time. SNS beam neutrons, on the other hand, will have a timing characteristic relative to the SNS operations. For this reason, Event 39 and Event 61 provide valuable information about those neutrons. Because the neutrinos are also coincident with the SNS beam, those beam-related neutrons are far more important to understand than the random room neutrons. MARS analysis is focused on measuring these beam-related neutrons.

Other environmental factors can complicate analysis. Neutrino Alley has enough concrete above it to provide 8 meters of water equivalent overburden which shields
against cosmic muons. These, like room neutrons, are random in time and are therefore easier to subtract in analysis. These muons are also used as a sort of calibration source because of their large energy depositions in MARS and the known time constant for decays of captured muons. Other environmental backgrounds can present a greater challenge.

The SNS produces neutrons via spallation of neutrons when high energy protons are fired into a mercury target. As a result of this process, spallation fragments are created in the target and those are removed through SNS operations. Many of those fragments are radioactive and may decay some time after the spallation reaction.

The SNS has a hot off-gas (HOG) pipe that runs the length of Neutrino Alley and is used to removed these fragments from the SNS target. These fragments may decay in the pipe and are a source of background for the experiments in Neutrino Alley. A large component of the background is 511 keV gammas from the annihilation of positrons on electrons. This interaction produces two 511 keV gammas. MARS is a large, unshielded plastic scintillator and therefore many of these gammas reach the detector and deposit their energy. The trigger threshold in MARS is around 1 MeV, and these gammas can pile up sufficiently so as to trigger the DAQ. These triggers are random, so they can be subtracted when making pairs, but they account for a large number of the DAQ triggers in MARS.

In order to measure the beam-related neutrons at the SNS, these backgrounds need to be handled and MARS must be characterized. Only then can neutron flux measurements be made with any degree of confidence. These prerequisite measurements are used to build up analysis of beam-related neutrons and ultimately to monitoring of beam-related neutrons.
Chapter 7

MARS CHARACTERIZATION

MEASUREMENTS

The configuration of MARS was altered from its previous operating configuration. In order to fit in Neutrino Alley, one of the two modules and the lead multiplicity volume were removed. For this reason, all neutrons are detected using the recoil technique where an incident neutron deposits its kinetic energy in a recoil event and then captures on the gadolinium in a capture event. This pair of events is separated from background pairs by using the capture-gating method. There are time and energy components that are a characteristic of the recoil and capture events that are different from random backgrounds.

In order to pick out neutron pairs from beam data, MARS must first be characterized to better understand efficiencies and energy scales. These measurements are then used to correct beam-related neutron data to more accurately measure the neutron flux.

Measurements of MARS characterization are detailed in this chapter. First, trigger efficiencies are measured near threshold to detail triggering at low energies. Second, the light yield and resolution are measured as a function of position in MARS. Light collection depends on where in the detector the energy deposition occurs and a map of this dependence is produced. Lastly, the neutron detection efficiency is measurement with a 14 MeV neutron source. All of these measurements inform simulations and are necessary for interpreting SNS beam-neutron data.
7.1 TRIGGER EFFICIENCY

The MARS DAQ is configured to trigger on PMT signals above threshold. This is in contrast to triggering on external timing signals, which is done in CENNS-10 for example. The reason for this is that the capture time of the thermal neutron is long at roughly 25 µs. So, while it is true that prompt neutron signals all arrive in a roughly 1 µs wide window, the capture signals arrive tens of microseconds later. Therefore, in order to use the capture-gate method to identify neutrons, triggering solely on SNS timing signals is not feasible.

The DAQ for MARS is configured to trigger on signals that deposit above roughly 1 MeV of light. This level is sufficiently below the ~8 MeV neutron capture energy but above 511 keV. There is a substantial background in Neutrino Alley from a hot off-gas pipe that emits 511 keV gammas at a very high rate. When collecting SNS beam data, pileup of the 511 keV gammas is a significant background but it is distributed flat in time and can therefore be subtracted. The roughly 1 MeV threshold strikes a balance between accepting as much signal as possible while not triggering at an unmanageable rate on backgrounds.

For energy depositions well above 1 MeV, the trigger efficiency is effectively 100%. Conversely, for energy depositions well below 1 MeV, the trigger efficiency approaches zero. The efficiency for triggers around 1 MeV can be measured as a function of energy. This is particularly important since a significant fraction of SNS beam-related neutrons deposit less than a few MeV of kinetic energy when thermalizing.

The trigger efficiency in this range is particularly important. The 511 keV pileup triggers account for a significant fraction of the total triggers in MARS. The energy deposited by many of the neutrons in recoil events is also near threshold. Pileup events can be subtracted from data, but below threshold recoils can never be recov-
ered. For this reason, careful measurements of trigger efficiency in this range are critical for accurate corrections to neutron rates.

7.1.1 EFFICIENCY MEASUREMENT SETUP

The MARS DAQ uses a finite impulse response (FIR) trapezoidal filter to handle triggering. Filter settings such as rise time, gap time, and FIR threshold can be adjusted to optimize the triggering. These settings are determined based on the characteristics of the plastic in MARS and are set to allow for efficient triggering on nuclear recoils and the gadolinium capture. The FIR setting is related to the energy of the threshold and it is this value that can be modified to change trigger energy thresholds.

In normal operations of MARS, the FIR setting is 300 ADC. By comparing trigger rates at this setting to trigger rates at other settings, the efficiency can be determined. This is because the threshold moves as the FIR setting is adjusted. When a rate at a particular energy is compared to the rate at the same energy with a different threshold setting, the difference in trigger efficiency is determined.

Data were collected at a number of FIR settings both above and below the normal operating setting of 300 ADC. Each run was 10 minutes in length and all other trigger settings were kept constant. The data were collected during a beam on period so that the hot off-gas background contributions would result in a high trigger rate at lower thresholds. Dead time results when trigger rates are too high for the DAQ electronics to handle and events which should trigger the DAQ are missed. This was seen in the data for the lowest threshold settings.
7.1.2 THRESHOLD DETERMINATION FOR UNITY EFFICIENCY

For a given threshold setting, above a certain energy level the trigger efficiency is effectively 100%. At that energy and above, moving the threshold down does not increase the trigger rate. A lower threshold results in more triggers, but those triggers are at the lower energies than are now passing the trigger settings. This can be seen in the spectra of the triggers from the two settings as in Figure 7.1. The spectra start to diverge around 16000 ADC units. Therefore, for a FIR setting of 280 ADC, and any value below 280 ADC, the trigger efficiency is roughly 100% for all triggers above 16000 ADC units.

As the FIR setting is lowered, the 100% efficient energy level decreases. In the limit that the FIR setting is zero, then perfect efficiency would be achieved at zero energy. Practically, measuring this is not achievable because of trigger rates and dead time. If the FIR setting were taken all the way to zero, the DAQ would be in a constant state of triggering and the electronics would be quickly overwhelmed. For all reference FIR settings, perfect efficiency is above a certain energy level and it is only that range, and not below it, that are necessary to consider.

Looking back at Figure 7.1, for FIR set at 300 ADC, MARS is roughly 100% efficient at triggering on integrated signals above 16000 ADC units. In order to know what the trigger efficiency is below 16000 ADC units, the threshold value is changed to progressively smaller values. This then maps out what the 100% efficient trigger rate is at each integrated energy value.
7.1.3 EFFICIENCY OVER ENERGY RANGE

When the trigger efficiency is less than 100%, the efficiency can be determined by dividing the counts at that energy by the counts that would have been there had the efficiency been 100%. Take as an example, for a certain FIR setting, if there are 1000 counts in a particular energy bin. For a different FIR setting where the efficiency in that bin is 100%, perhaps there were 5000 counts in that bin. The trigger efficiency for the original FIR setting, at that energy, is then $1000/5000 = 20\%$.

In Figure 7.2 the teal curve is the spectrum for the FIR=300 ADC setting. At roughly 16000 ADC units, the counts in each bin are similar to the counts for lower threshold settings because the efficiency at FIR=300 ADC is approaching 100%. At lower energies, the counts in each bin are a fraction of the counts for lower threshold settings. This is because the efficiency for FIR=300 ADC is approaching zero at those energies. It is this range of energies, where the efficiency is between zero and unity, where the efficiency should be measured.

The FIR=70 ADC spectrum is used as the reference spectrum. At this setting, it was determined that there was a little dead time in the data collection, but this can be accounted for by scaling the spectrum since dead time affects all energy ranges equally. A 50% dead time, for example, could be accounted for by scaling the spectrum by a factor of 2. The actual dead time was only a few percent at the 70 ADC FIR setting. Then, the FIR=70 ADC setting was determined to be 100% efficient above 5000 ADC units. This is because the scaled counts in the 5000 ADC bin were in agreement with the scaled counts in the same bin at FIR of 60 ADC. Below 5000 ADC units, the counts in each energy bin for FIR=300 ADC were vanishingly small and therefore the trigger efficiency below 5000 ADC units is considered to be zero.

For a particular FIR setting the trigger efficiency can be determined for each
energy bin by dividing the counts in each bin by the counts in the corresponding bin for a reference spectrum with 100% efficiency in each bin. A true 100% efficient spectrum at all energies is unachievable but can be approximated by a low-threshold spectrum above a certain energy range.

The trigger efficiency for FIR=300 ADC as a function of energy can be seen in Figure 7.3. This was determined by dividing each bin in the FIR=300 ADC spectrum by its counterpart in the scaled FIR=70 ADC spectrum between ADC values of 5000 and 16000. The result was then fit with an error function. This was chosen because the data match that shape quite well and it has the correct physical behavior - it can be made to approach 0 at the lower end and 1 at the higher end. The result of the fit is seen in Equation 7.1

\[
T.E. = \frac{1}{2} \cdot \frac{1}{2} \cdot erf \left( \frac{11890 - E}{3593} \right)
\]

where T.E. is the trigger efficiency and E is the integrated energy in ADC units. The values of \( \frac{1}{2} \) were fixed to maintain the appropriate bounds of the curve but the other values come from the best fit of the curve to the data.

This efficiency is important to consider in simulations. In order to determine whether or not a simulated energy deposition will trigger the DAQ, the efficiency at that energy must be known. The results in Figure 7.3 are used in all simulations of MARS data. This means that for a simulated event that falls in this energy range, trigger rates depend on this result. Above and below this range the trigger rates are taken to be 0% and 100%, respectively.
Figure 7.1: Spectra from two threshold settings. The 100% efficient level is determined by looking at where the spectra diverge. Above this level, the trigger efficiency for the lower threshold setting is effectively unity.

Figure 7.2: The unity efficiency is traced out by systematically decreasing the FIR setting. The teal spectrum is from FIR=300 ADC, and the spectra with ever-increasing counts are for the lower threshold settings. The lowest threshold settings are 100% efficient above energies around 6000 ADC units. Comparing the counts in each energy bin for FIR=300 ADC to those lowest threshold spectra gives the trigger efficiency for FIR=300 ADC as a function of energy.
7.2 LIGHT YIELD AND RESOLUTION

MARS is a large plastic detector. In order for an energy deposition to trigger the DAQ, light from the interaction must travel through the plastic, to the light guide, and then to one of 16 PMTs. Interactions that deposit a lot of light near one of the PMTs are more likely to trigger the DAQ than those where the interaction is low energy and far from any PMT. Relative light yield and resolution, as a function of position in the detector, are important for understanding the response of the detector.

The light yield is linear in energy in the plastic scintillator in MARS [15]. This is true for energy ranges that are of interest in nearly all scintillating plastics. This linearity means that the integrated values from the DAQ give an energy, in ADC units, that is proportional to the detected energy in normal energy units, such as keV. The “slope” is the relationship between this light yield in ADC units and the energy on the event in keV. This slope is a function of position, because an energy deposition near a PMT will result in a greater light yield than an equivalent energy
deposition that is far from any PMT. Therefore, it is critical to measure this unit conversion as a function of position.

In addition to light yield, energy resolution is a function of position. This energy resolution can be modeled by a Gaussian, where the standard deviation of the Gaussian, \( \sigma \), depends on the energy of the interaction. Standard forms for \( \sigma \) for energy resolution contain terms that depend on the energy, the square root of the energy, and a constant. However, for energies in the range of interest, only the term proportional to the square root of the energy is needed \[48\]. The constant needed to define the Gaussian shape is here referred to as \( \alpha \).

\[
LightYield = m \times E \tag{7.2}
\]

\[
\sigma = \frac{1}{2.355} \sqrt{E} \times \alpha \tag{7.3}
\]

where \( m \) is the slope relating light yield to energy deposition, \( \sigma \) is the Gaussian width of the energy resolution, and \( \alpha \) is the constant that sets this width.

### 7.2.1 SETUP AND DATA COLLECTION

A cobalt-60 source was used for the measurement of light yield and energy resolution because of the energy of the emitted gammas (1.17 and 1.33 MeV) and the activity of the sources available. The low-energy gammas are easily collimated, which is ideal for making position-dependent measurements, and are above threshold and similar to one another. All of this makes data collection simulation less complicated than other gamma emitters.

The roughly 1 MeV gammas would produce full-energy depositions that are above
the MARS threshold settings, but many of the Compton scatters would fall below threshold. Additionally, in order to aid in matching simulation to data, it is ideal that spectrum features are sufficiently far from threshold effects as these can be difficult to model. For this reason, the threshold setting for this measurement was lowered such that the Compton edge from the gamma scatters was sufficiently far from the threshold.

One half of a standard lead brick was machined to hold the cobalt-60 button source and to provide a collimated window to the detector as seen in Figure 7.4. An aluminum stand was constructed to provide a way to position the collimated source in front of MARS in several locations. Data were collected in 10-minute runs in each of 20 source locations in a 5×4 grid in addition to background runs done before and after the source runs.

### 7.2.2 SIMULATION AND FITTING

Rebecca Rapp, a member of the COHERENT Collaboration, produced a simulation for each of the 20 source run locations. The simulation was done with GEANT4 and the energy depositions in MARS were saved in the simulation output file. For each location, the simulation is compared to data to measure the light yield and energy resolution in MARS as a function of position.

For each of the 20 source locations a data file and a binned simulation file are used as inputs to a RooFit analysis. Additionally, a sourceless background file is included for the fit and backgrounds are known to high accuracy. The simulated data are smeared and scaled for a pair of values for the slope and alpha. The amplitude of that result is floated and added to the background data to compare to the source data. \( \chi^2 \) is calculated, and then the procedure is repeated for another
pair of values for the slope and alpha. The pair of values that minimizes the $\chi^2$ are saved as best-fit values. An example of one of those best fits can be seen in Figure 7.5.

Figure 7.4: Experimental setup for light yield and resolution determination. The lead brick allows for collimated exposure and the stand provides a way to move the source around.
Figure 7.5: Result of best-fit values from fit to one of 20 source location simulations. The values for slope and alpha are used to smear and scale simulations for matching data.

Each of the 20 locations form a 2-dimensional map of the front of the detector. The best-fit values for slope and alpha form the basis of the map for the entire surface. Linear interpolation is used between data points and the resultant pair of maps (one for slope and one for alpha) serve as inputs to all MARS simulations. The pair of maps for alpha and slope can be seen in Figure 7.6 and Figure 7.7 respectively.
Figure 7.6: Full 2-dimensional map of the alpha variable related to energy resolution in MARS.
For simulations, energy depositions are done in natural energy units such as keV. In data, energies are computed by integrated accumulator sum values and are in ADC units. This result gives the conversion factor that allows for simulation to model real data. Combined with the near-threshold trigger efficiencies, simulation of neutron source runs can start to be modeled where recoiling nuclei produce signals in the energy range of interest.

7.3 NEUTRON DETECTION EFFICIENCY

In order to detect a neutron with MARS, several criteria must be met. The neutron must be low enough in energy to thermalize in the plastic. Otherwise, the neutron punches through and would not pass the capture-gating analysis cuts. Second, the
neutron must capture on the gadolinium before leaving the detector. Lastly, the capture time and detected capture energy, E2, must be in the time and energy range cuts set on those variables.

In SNS beam on data, there are going to be neutrons that pass through MARS but do not pass all of this criteria. For that reason, to get a good measurement of neutron rates, detection efficiencies must be understood and measured. This means measuring the capture efficiency for some neutron population and extrapolating to all energies. Simulation must be used to extrapolate from single measurements to the entire neutron spectrum.

7.3.1 NEUTRON EFFICIENCY BASICS

In order to measure neutron detection efficiency, an ideal neutron source would have several characteristics. First, it would be monoenergetic so that analysis can be done and compared to simulation knowing the energy of the neutron on an event by event basis. Second, timing information of the neutron would be useful for knowing when the neutron should show up in the detector. And lastly, directional information is useful if analysis will be done on a position-dependent basis.

Missing any of these elements would make an efficiency measurement more difficult. A californium source, while generally easier to procure, makes analysis difficult because the neutrons are not monoenergetic, time-tagging is challenging, and there are gammas associated with the decay that can be problematic. A neutron beam may have all of the desired characteristics, but rates might be a problem and it requires moving the detector.

An ideal source is portable, intense, monoenergetic, and time-tagged. With these characteristics, each neutron arrival time and energy is known. Therefore, if the neutron passes analysis cuts then it is “detected.” If it does not pass analysis cuts, or if
it does not trigger the DAQ, then it is not detected and is part of the inefficiency of
the detector and analysis.

7.3.2 DT GENERATOR SETUP

In order to measure the neutron capture efficiency in MARS, a DT generator was
used. DT generators produce neutrons via the reaction between deuterium and tri-
tium which produces helium and a neutron. This reaction is monoenergetic and the
resulting neutron has an energy of 14.1 MeV. The setup of the DT generator in front
of MARS can be seen in Figure 7.8.
This DT source generated neutrons at roughly 10000 Hz. DT runs were an hour in length and at that rate MARS saw many many years worth of neutrons when compared to SNS beam neutron rates. The DT generator electronics were integrated into the MARS DAQ and the additional channels providing timing and directional information for the neutrons.

The DT generator is equipped with a pixellated alpha backing detector which gives positional information of the helium which is produced in the DT reaction. The alpha particle and neutron are back-to-back because they result from the one-body decay of helium-5. By detecting the alpha particle in the pixellated backing...
detector, both timing and directional information for the neutron are known.

### 7.3.3 PAIR MAKING IN DT DATA

Like with all neutrons, detection of neutrons from the DT generator relies on the capture-gating method. For this to work, pairs of triggers are formed from all of the raw triggers. When MARS is collecting SNS beam data, the relevant timing signal comes from the SNS Event 39. All trigger timing is measured relative to that signal. For the DT neutrons, the relevant timing information comes from the alpha backing detector. This signal was used in place of Event 39 in analysis - so the ‘t’ variable for time is the time since an alpha backing detector trigger instead of since an Event 39.

The DT generator produced neutrons at around 10000 Hz. This means that there is a alpha trigger at that rate. The SNS, on the other hand, operates at 60 Hz. When looking at neutrons from the SNS beam, they will always belong to the SNS timing signal that immediately preceded the neutron. This may not be true with the DT generator because the capture time (roughly 25 $\mu$s) is comparable to the time between neutron production at 10000 Hz.

For that reason, pairs of signals must be made relative to not only the most recent alpha trigger, but also triggers that came before the most recent one. However, the time of flight for the neutrons is quite small and a narrow window around each alpha trigger can be drawn for when the first signal is expected to arrive at the detector. Pairs of triggers and their relative timing can be seen in Figure 7.9. The horizontal axis represents time and there are two alpha triggers which are each followed by PMT triggers in MARS. Neutrons will always have the first trigger of the pair in a small window following an alpha detector trigger. The window is only 70 ns wide which is
very small relative to the capture time of the neutron.

Figure 7.9: Pairs of triggers in MARS which are characteristic of neutrons have a particular signature. The first trigger from the pair is in a small time window immediately following an alpha trigger, represented by an “A” here. These are in contrast with pairs that do not have that signature to compare signal to background and measure detection efficiency. The red arrows denote a pair of triggers.

Similar to SNS beam data, the time since an alpha trigger variable “t,” the time between PMT triggers “dt,” the energy of the first trigger “E1,” and the energy of the second trigger “E2” for all pairs is written out after data processing. Some of these pairs are actual prompt energy deposition from the neutron scattering in the detector followed by capture on the gadolinium. Other pairs of signals could be a scatter signal paired with some background signal, or a background signal paired with a capture, and so on. In order to measure detection efficiency, signal and backgrounds must be separated.
7.3.4 IDENTIFYING NEUTRON PAIRS

Figure 7.9 shows pairs of signals that may or may not be the prompt neutron followed by capture signals that are important. In order to separate signal from background, the background contribution needs to be removed. First, all prompt-capture pairs will have a prompt signal immediately following a alpha backing detector trigger. This population emerges from selecting on the “t” variable. In Figure 7.10 the peak between 425 ns and 525 ns is where all of the prompt-capture neutrons will show up. All pairs outside of this window can be removed from counting.

The cut on “t” removes those pairs that do not look like neutrons from Figure 7.9. Prompt-capture neutrons will also have timing and energy characteristics that are different from backgrounds. The “dt” variable represents the time between the signals and this variable is flat for backgrounds. Any time component in plotting this variable can be attributed to signal. Likewise, the energy of the prompt and capture signals, “E1” and “E2,” will be different for prompt-capture pairs than for backgrounds.

In identifying neutrons from the SNS, cuts are made on “dt” and “E2.” These variables are characteristic of the capture process and are the basis for the capture-gating method of identifying neutrons. For that reason, in a neutron-rich sample these variables are the source of information needed to identify the neutrons.
Figure 7.10: The time, relative to an alpha trigger, of the first signal in a pair of signals. Signals from prompt neutrons will all have timing relative to the backing detector signal which are consistent with one another.

Figure 7.11 is a two-dimensional plot of “dt” and “E2” for pairs of signals with “t” in the appropriate window described previously. This plot represents both signal (prompt-capture pairs) and background. In order to subtract background from this sample, the characteristics of the “dt” variable are used.

Random backgrounds are flat in “dt.” This can be seen in Figure 7.12. This is “dt” for a small range of “E2” values and has the flat and exponential components that are consistent with a flat background and exponential capture time.
Figure 7.11: Two-dimensional plot of “dt” and “E2.” These are the variables used to separate prompt-captures pairs from backgrounds.

Figure 7.12: The “dt” variable for a single “E2” bin. The two components of “dt” are a flat background and an exponential which is consistent with the neutron capture time.

For each bin in “E2” the plot of “dt” will look like Figure 7.12. The background contribution can be subtracted by accounting for the flat component in “dt.” For each bin in “E2” the last 10 bins in the projection in “dt” is averaged and that value
is subtracted from each bin. For example, Figure 7.12 is “dt” for $30.0 \times 10^3$ ADC $< E_2 < 30.5 \times 10^3$ ADC. The average value in the last 10 bins in “dt” is 1215 counts. In Figure 7.11 1215 counts is subtracted from each bin in this “E2” range. In this way the background subtraction is done for each “E2.” The result of this background subtraction is shown in Figure 7.13.

Figure 7.13: Two-dimensional plot of “dt” and “E2” after background subtraction. Finding efficiencies, as a function of cuts on these variables, becomes simple subtraction and division.

7.3.5 EFFICIENCY CALCULATIONS

The purpose of measuring neutrons from the DT generator is to measure the detection efficiency of MARS. Neutrons which arrive at the detector may go undetected for a number of reasons. The prompt signal may be below threshold, the neutron may escape without capturing, or the pair of signals may not pass cuts used to optimize signal over backgrounds. All of these things can result in an undercounting of neutrons in SNS beam data. All of these inefficiencies can be accounted for in a signal efficiency measurement.
For any set of cuts on “dt” and “E2” the MARS efficiency is determined by integrating Figure 7.13 over that range. This is the numerator in the efficiency calculation and represents neutrons which are detected and pass cuts on “dt” and “E2.” The numerator is the total number of detected neutrons for these cuts. The denominator is the total number of neutrons which should have been detected by MARS. This number is determined by counting all alpha backing detector hits. For every hit there is a neutron that should be detected in MARS. Any neutrons which go undetected, for any of the reasons described previously, will then not contribute to the integral.

This process can be repeated for any set of cuts on “dt” and “E2.” Therefore, Figure 7.13 can be used to determine cut efficiencies for any set of cuts. For example, 0.0 µs < dt < 62.0 µs and 31.5 x 10^3 ADC < E2 < 52.5 x 10^3 ADC was used as an initial set of cuts for beam neutrons. For this set of cuts, the detection efficiency in MARS is 3.9%.

This result is specific to 14.1 MeV neutrons. Simulations are underway to extrapolate this result to all energies of interest in Neutrino Alley. This result coupled with the results of the light yield map allow for simulations to map all of the efficiencies of interest.
Chapter 8

NEUTRON MONITORING

The primary goal in deploying MARS at the Spallation Neutron Source is to measure and monitor neutron fluxes in various locations in Neutrino Alley. Different locations will have different neutron fluxes because the distance to the SNS target varies in addition to the amount of concrete between the target and the location. The SNS also operates at different power settings and it is therefore important to characterize the neutron flux in relation to beam power. This is an ongoing effort and improvements to measurements are being made as more data are collected.

8.1 DATA COLLECTION AND PROCESSING

MARS was deployed to the SNS in September 2017 and has collected beam data nearly continuously since that time. The detector was located in its initial position from deployment until January 2019. At that time it was then relocated to another position in Neutrino Alley and remains there as of March 2021.

In order to measure a neutron flux with any significance requires exposure to SNS beam-on for a minimum of three months. This is due to the low flux and efficiency of the detector. The focus of this analysis will be on the data collected in the initial location during the calendar year 2018. Over that year, the SNS was on for roughly half of the year and off for the remainder. The top panel in Figure 8.1 shows the average daily SNS beam power from April 2018 through December 2108. For most of June and July the beam was at $1.3 \times 10^3$ Joules/s and in September and October
it was $1.4 \times 10^3$ Joules/s. Outside of these two periods are periods where the SNS beam was off. These show up as the average daily beam power at zero.

Data runs were set for 24 hours at a time. The DAQ was configured to write out a new file after 24 hours of continuous data-taking and to start a new run. The daily file size and trigger rates are shown in the second and third panels in Figure 8.1. The file size should be proportional to trigger rates and that is confirmed by comparing the second and third panels to one another. Trigger rates are significantly lower during the beam-off periods than the beam-on periods as expected.

There is a gradual decrease in trigger rates over time, even when SNS beam power is mostly constant. All DAQ settings were kept constant for the entire run and therefore the slow change in trigger rates is a physical phenomenon and not a result of a change in data collection. The PMT baselines shown in the bottom panel of Figure 8.1 show that the baseline values were constant over time. This means that the gradual decline in trigger rates can be attributed to a gain shift over time. Gain shift occurs when light collection changes over time. As the light collection decreases, low energy events that would have previously triggered the DAQ no longer do so because they are now below threshold. This shows up as a decrease in rates even though backgrounds have remained constant.
Figure 8.1: Average daily beam power for most of 2018. The file size and trigger rates decline while the beam power stays constant. This is due to the gain shift in the detector. Figure from B. Cabrera-Palmer.

8.2 DATA PROCESSING

A MARS data file consists of binary data representing a series of events from one of the two types of triggers of the DAQ. The first type of trigger is from one of the two SNS timing signals which are referred to as Event 39 and Event 61. The second type of trigger results from light collection above threshold in one of the four groups of PMTs. These two types of events are written out sequentially in the data stream.
and is recorded with a timestamp in universal time.

The SNS timing events receive an offset to their universal time. The reason is to avoid any issues that may arise from having beam-related triggers very close in time to the SNS timing triggers. The Event 61 triggers are offset by 900.0 \( \mu s \) and Event 39 triggers are offset by 800.0 \( \mu s \). The Event 61 triggers indicated that the SNS beam spill does in fact contain protons on target. The Event 39 trigger is used for timing. Therefore, a trigger in MARS that is now 900.0 \( \mu s \) after an Event 61 and 800.0 \( \mu s \) after an Event 39 would be coincident with the SNS beam.

Raw hits are processed by using the accumulator sum values to do a baseline subtraction calculation of the energy of the PMT-triggered events. This energy, in ADC units, represents the amount of light collected for that event. The time information for this raw hit is also saved.

The final step in processing involves forming all pairs of raw hits. Each pair is characterized by three time variables and two energy variables. The time since the previous Event 39, the time since the previous event 61, and the time between the pair of raw hits then describes all of the timing information for the pair or triggers relative to SNS timing information.

In order to identify neutrons in SNS beam data with MARS, the capture-gate method is used on all pairs of triggers. This means the next step in processing data is to form all pairs of triggers. For all pairs of triggers, the variables “t,” “dt,” “E1,” and “E2,” are saved in addition to the time since the previous Event 61. All of this information for all pairs is written out to a ROOT file for ease of analysis.
8.3 FINDING THE SNS BEAM

The SNS beam operates at 60 Hz. By saving the time variable, “t,” as the time since the previous Event 39, the maximum time then for any pair then is 16.67 ms. When plotting the variable for all pairs for a beam-on period, there is no excess seen in any time window. The reason for this is that the trigger rate from the 511 keV background pileup is quite large and hides any significant signal.

In order to find the beam in time, cuts on the data are required. These cuts, described later in this chapter, reduce the background significantly and the beam timing appears. Figure 8.2 shows the “t,” or time since the previous Event 39, for all pairs after these cuts. There is a clear excess that emerges at 800 µs. This is a result of the software offset that was used in processing. This bin is in fact precisely coincident with the SNS beam. Figure 8.3 is the same as Figure 8.2 but zoomed in around the region of interest.

Figure 8.4 is a fit of the counts in each bin from Figure 8.2. The counts in background bins have a Gaussian distribution around a mean which here is 523.7 counts. The counts in the beam-coincident bin, from 800-802 µs, is 712 and is a 7.28σ excess. By cutting on a set of variables in the pairs data, the timing of the SNS beam emerges. These cuts are selecting for something that is coincident with the beam. That something is assumed to be neutrons.
Figure 8.2: The 60 Hz nature of the SNS timing signal can be seen by plotting the time since the most recent Event 39 for all pairs. The excess in a single bin emerges once cuts on pair data are made. Prior to these cuts, background rates are so high that no excess appears.

Figure 8.3: A zoomed in view of Figure 8.2. The excess appears in the expected time bin related to Event 39. The software offset applied in processing moves the coincident time away from zero as expected.
Figure 8.4: A fit of the counts in each time bin from Figure 8.2. The 712 counts in the bin of interest represents a $7.28\sigma$ excess from the fit mean. Other large deviations from the mean are consistent with expectations.

8.4 NEUTRON CUTS

In order to identify neutrons in the SNS beam data, cuts on the variables are required to see any signal. The time, "t," can be used to define two windows - one is coincident with the beam and the other is not. For this, the in-beam window is defined to be from 800-802 $\mu$s. This exactly accounts for the software offset described previously. The out-of-beam window is defined to be from 1-15 ms. This is a much wider window. For this reason, in comparisons for in-beam to out-of-beam windows a scaling factor of 14 ms over 2 $\mu$s, which equals 7000, is used.

The “E1” variable is not used to identify neutrons. The reason for this is that MARS is being used to measure “E1.” The assumption is that nothing is known about “E1” beforehand. Cuts on “E1” would select some of the neutron population but leave out other parts. Therefore, no cuts are used on “E1” to identify neutrons.

The timing and capture energies are known for neutrons in MARS. MARS has a neutron capture time of roughly 25 $\mu$s and the gadolinium capture releases 7.9
MeV in energy. Therefore, the “dt” and “E2” variables are very useful for selecting neutrons. Cuts on these variables alone do not reduce the backgrounds enough to see the neutron signal emerging in the “t” variable. The combination of cuts, however, give the significant result shown in Figure 8.2.

In order to quantify the quality of the cuts on “dt” and “E2,” the “significance,” $S$ is defined as:

$$ S = \frac{signal}{\sqrt{signal + background}} $$  \hspace{2cm} (8.1)

For a set of cuts on “dt” and “E2,” the background is taken to be the number of counts that pass those cuts and is in the out-of-beam window. This number is scaled due to the amount of time in the in-beam window compared to the out-of-beam window. The signal is taken to be the number of counts that pass the “dt” and “E2” cuts in the in-beam window minus the background counts.

In order to identify an optimal set of cuts, all values of “dt” and “E2” are stepped over, calculating the significance for each set, and the set that maximizes the significance is taken to be the optimal set. There are 4 values that are floated here: the lower bound on “dt,” the upper bound on “dt,” the lower bound on “E2,” and the upper bound on “E2.”

The in-beam and out-of-beam distribution of “dt” and “E2” can be seen in Figure 8.5 and Figure 8.6, respectively. The out-of-beam population in Figure 8.6 has been appropriately scaled down by the factor of 7000. Cuts on “dt” and “E2” can be imagined as a square drawn on the 2-dimensional plot. Counts in the out-of-beam window, in the square, are counts that would pass the cuts for that time window. As the size and position of the square are changed, the number of counts that pass the cuts changes. The square that optimizes the significance is the optimal set of cuts.
The set of cuts which maximizes the significance is $0.0 \mu s < dt < 62.0 \mu s$ and $31.5 \times 10^3$ ADC $< E2 < 52.5 \times 10^3$ ADC. The significance value for this set of cuts is 7.04. This was done for all 2018 data. It is this set of cuts used to produce Figure 8.2. These cuts make sense in the context of what is known about MARS and the capture-gating method. 62.0 $\mu s$ is between 2 and 3 capture times for MARS, and the energy scale for E2 is consistent with a few MeV in MARS.
8.5 MONITORING NEUTRONS

Neutrons are clearly showing up in a year’s worth of data. One objective for MARS is to monitor neutrons over time. The rates in Neutrino Alley are low enough that this cannot be done on a daily basis, but could be done on a monthly or bimonthly basis.

Using the Michel electron to set the energy scale, “E” can be converted approximately from ADC to MeVee. The unit MeVee is “MeV electron equivalent.” Any event which produces the same amount of light as a 10 MeV electronic recoil has deposited 10 MeVee of energy. This may be a result of a nuclear recoil. Generally, nuclear recoils of higher energy release equivalent light to lower energy electronic recoils.

Figure 8.7 and Figure 8.8 show the “E1” spectrum for June and November of 2018. The blue lines are the E1 spectra for pairs that pass the optimal cuts on “dt” and “E2” and are in the in-beam timing window from 800-802 µs. The red curves are pairs that also pass the optimal cuts but are in the out-of-beam window. This count is scaled by the factor of 7000 to account for window widths.

The left panels show these spectra. The inset is identical to the main plot but is zoomed in and has different binning. The right panels show residual counts. This represents the spectrum for E1 during that month. This is done for all months in 2018. All months with beam-on show a clear excess in the “E1” spectra and beam-off months are consistent with zero.

This strategy represents a way to track neutrons as a function of time with MARS. By comparing one time period to another, potential changes in rates and energies may be observed. This is difficult on short time scales because of rates, but can be achieved for longer exposure times. MARS has also been moved since 2018. This
allows for comparison of this data to the data from its current operating location.

**Figure 8.7:** The left panel is the pairs that pass the optimized cuts for neutrons which are in-beam (blue) and out-of-beam (red) in June 2018. The inset of the left plot is the same as the larger plot but with different binning. The right panel is the difference between the blue and red from the left panel. The residual, the difference between the blue and the red, is the number of pairs in that energy bin in excess of backgrounds. This is the number of neutrons detected.
Figure 8.8: The left panel is the pairs that pass the optimized cuts for neutrons which are in-beam (blue) and out-of-beam (red) in November 2018. The inset of the left plot is the same as the larger plot but with different binning. The right panel is the difference between the blue and red from the left panel. The residual, the difference between the blue and the red, is the number of pairs in that energy bin in excess of backgrounds. This is the number of neutrons detected.

A primary goal for MARS to measure the neutron flux over time. Detailed spectral information requires longer exposures, but rates can be monitored over time without the detailed spectra. This is due to the fact that rates rely only on total counts.

Figure 8.9 shows the total counts that pass the optimized cuts on “dt” and “E2” for selecting neutrons. Each month is normalized by beam power and number of days. For example, the average daily beam power in October was higher than the beam power in June as seen in Figure 8.1 and there is an extra day in October relative to June. Doing this effectively normalizes by beam energy delivered to the target. The number of neutrons produced at the SNS is assumed to be proportional to beam energy delivered for all other detectors in Neutrino Alley.
Figure 8.9: The total number of pairs that pass optimal cuts for neutrons in beam in black. The number of pairs that pass the same cuts but are out-of-beam is in red. The difference between the two, the residual, is in blue. Months with many beam-on days have greater residual counts. Each month is normalized by beam power and total number of days.

8.6 NEUTRON FLUENCE

Figure 8.10: The left panel is the pairs that pass the optimized cuts for neutrons which are in-beam (blue) and out-of-beam (red) for all 2018 beam-on data. The inset of the left plot is the same as the larger plot but with different binning. The right panel is the difference between the blue and red from the left panel. The residual, the difference between the blue and the red, is the number of pairs in that energy bin in excess of backgrounds. This is the number of neutrons detected.
The stability of MARS allows for flux measurements if exposure time to the beam is long enough. For the 2018 data, more than 6 months of data with the SNS beam on was used to count neutrons. These beam-on periods are included in Figure 8.10. Integrating the residual plot in Figure 8.10 gives a total count of beam-related neutrons equal to $179 \pm 27$ neutrons. This is a roughly 15% statistical uncertainty on the neutron count.

The DT generator data were used to determine the detection efficiency of MARS for 14 MeV neutrons. This value is 3.9%. It does, however, depend on the cuts used in analysis and on neutron energy. As more data are collected with MARS, and the optimal cuts on “dt” and “E2” change for different periods, the detection efficiency will change.

In private communications with R. Rapp, her GEANT4 simulations show that detection efficiency in MARS increases and then decreases as the neutron energy decreases. For 5 MeV neutrons, the detection efficiency is 54% higher than the 3.9% at 14 MeV. For energies a little higher than 14 MeV, the efficiency decreases. Therefore, it is reasonable to use 3.9% as rough estimate of the efficiency for neutrons in the lowest energy bins in Figure 8.10. This energy is the deposited energy from the neutrons. The uncertainty on this efficiency value is conservatively set at 54% and is the dominant component of any systematic uncertainties. Simulations are underway to put tighter constraints on the efficiency for all energies and will be included in a future paper.

The SNS operates at 1.4 MW under optimal conditions. The beam is off at times even during long, stable periods for things such as maintenance and accelerator studies. During the period spanned in Figure 8.10, from May 2018 through November 2018, the total amount of energy delivered to the target was $14.70 \times 10^{12}$ J. Given that the cross-sectional dimensions of MARS are 100 cm x 75 cm, the total neutron
fluence for MARS during this period of 415 neutrons/m$^2$/10$^{12}$J on target. The uncertainties on this number are the 15% statistical and 54% systematic uncertainties mentioned previously.

Table 8.1: Fluence measurements by neutron detectors in Neutrino Alley. MARS was in the location known to have the lowest neutron rates. The second NSC measurement and the SciBath measurement were both done in the alcove which is known to have the highest neutron rates in Neutrino Alley. The first NSC measurement was done in a location between the alcove and the MARS location. With exposure times similar to the 2018 run, MARS should be able to improve upon previous measurements in other locations. The NSC and SciBath numbers from B. Cabrera-Palmer.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Fluence (neutrons/m$^2$/10$^{12}$J)</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSC</td>
<td>1500</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>NSC</td>
<td>76000</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>SciBath</td>
<td>3700</td>
<td>19%</td>
</tr>
<tr>
<td>MARS</td>
<td>415</td>
<td>15%$<em>{stat} + 54%</em>{sys}$</td>
</tr>
</tbody>
</table>

The Neutron Scatter Camera (NSC) and SciBath detectors were used to make other fluence measurements in Neutrino Alley. The results of those measurements can be seen in Table 8.1. While the fluence measurement here is lower than the previous measurements, MARS was intentionally located in a location in Neutrino Alley that has very low neutron rates. The fluence was expected to be lower than the other fluence measurements. This measurement confirms precisely that.

The SciBath measurement was performed in the alcove in the location of the CENNS-10 detector. This result was used in CENNS-10 analysis and represents an opportunity for MARS to improve that result. A long exposure in the alcove could result in a MARS measurement of the neutron fluence with statistical uncertainties below 10%. Systematic uncertainties will shrink with further simulation of the detection efficiency.
8.7 FUTURE MARS WORK

MARS is continuing to collect data in the second location in Neutrino Alley. Problems with SNS operations, and the COVID pandemic, resulted in a longer-than-expected exposure time in that location. These data are processed regularly and will result in a second measurement with MARS in Neutrino Alley which will improve upon the results here.

MARS will eventually move to a new location in Neutrino Alley. By moving to new locations, the flux can be mapped throughout the entire Alley. This is critical as new CEvNS detectors come online in new locations and old detectors are retired from their current ones. MARS provides a tool to not only measure the flux in specific locations, but to map the entirety of the Neutrino Alley. And as systematic uncertainties in characterization, MARS will put tighter limits on the neutron flux throughout Neutrino Alley.
Chapter 9

CONCLUSION

MARS takes advantage of the capture-gating method to identify neutrons in Neutrino Alley at the Spallation Neutron Source. Neutrons have been identified for the 2018 beam-on data and a first pass at measuring the spectrum is shown. The rates in MARS allow for sufficient statistics to make a spectral measurement after a few months of beam-on exposure in any location in Neutrino Alley.

Many of the neutrons deposit energy in the lowest detectable energy range. For this reason, trigger efficiencies are needed to understand how many neutrons are actually passing through MARS at these lower energies. The trigger efficiency was measured at these lower energies and is now included in all simulations for neutron measurements.

The light yield and resolution are a function of position because MARS is a large plastic scintillator with PMTs on the sides. Light collection from energy depositions near the edges of the detector will differ from interactions near the middle. The light yield and resolution are measured for MARS as a function of position. Those results are used in simulation to better reflect those differences.

Being a large plastic scintillator that requires two signals above threshold, MARS loses some efficiency for neutron detection. The high background levels near threshold make identifying low-energy events particularly challenging. Many of the neutrons in Neutrino Alley deposit energy near this threshold level. All of these things contribute to imperfect efficiency for neutron detection with MARS.

These efficiencies can be accounted for if properly measured. For a set of cuts used
to optimize for beam neutrons, the detection efficiency was measured to be between five and six percent. The neutron detection efficiency is measured with MARS and is easily generalized for any set of cuts on the experimental variables. This allows for corrections to measured neutron spectra. These efficiencies will be used for improvements to the measured neutron spectra.

MARS collected data in its original location throughout the entirety of 2018. During that time, over 6 months of beam-on data from nearly $15 \times 10^{12}$J of energy delivered to the mercury target produced $179 \pm 27$ detected neutrons in excess of backgrounds. The spectrum is dominated by neutron energy depositions below 10 MeV in the location, as expected. Using detector efficiencies, the fluence is compared to other neutron detectors from Neutrino Alley and while rates are lower than for other detectors, the location of MARS was known to have lower neutron rates. The measured fluence is $415 \text{ neutrons/m}^2/10^{12} \text{J on target } \pm 15\%_{\text{stat}} \pm 54\%_{\text{sys}}$.

Characterization measurements here give an understanding of MARS detector response. These measurements are critical for improving rate and spectral measurements with the detector which are ongoing. As more data are collected with MARS, these characterization measurements become increasingly essential. As MARS continues to map the neutron spectra, and the results of these measurements improve, these measurements will be critical inputs for other detectors in Neutrino Alley. As MARS shrinks the uncertainties on neutron fluxes in Neutrino Alley, all of the CEvNS detectors will benefit. MARS is even capable of identifying potential neutron-arrival time differences in different locations.

This work is a first measurement of the neutron fluence in that location in Neutrino Alley. The future germanium CEvNS experiment will be located here and this measurement may provide input for shielding considerations. Subsequent measurements here with MARS can confirm that the neutron rate is consistent over time.
The characterization measurements here will be used in analysis of all MARS data going forward.

The alcove location in Neutrino Alley where the CENNS-10 detector made the second CEvNS measurement represents a new location for MARS to improve on previous work. The beam neutrons represented more than half of the 8.5% systematic uncertainty on the CEvNS measurement. As more data are collected with CENNS-10, MARS can operate nearby and monitor neutron rates. MARS should be able to measure the neutron fluence in that location with comparable precision to SciBath with roughly six months of exposure.

Fully mapping the neutrons in Neutrino Alley allows for greater background reduction for all of the COHERENT CEvNS detectors. This background is coincident with the beam, and is therefore incredibly important to understand. This background monitoring is critical alongside CEvNS measurements as COHERENT pursues the goal of mapping CEvNS across the wide range of $N^2$ possibilities. The goal for MARS is to reduce uncertainties around beam-related neutrons in the prompt window such that these uncertainties are not the dominant systematic uncertainty in any of the COHERENT CEvNS detectors in Neutrino Alley.

\[
G_V = (g_V^p Z + g_V^n N) F^{V}_{\text{nuc}}(Q^2) \quad (9.1)
\]

\[
G_A = (g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)) F^{A}_{\text{nuc}}(Q^2) \quad (9.2)
\]


[33] https://twitter.com/theLeadNube


[42] https://neutrons.ornl.gov/sns


