

# Measurement of Neutrino-Induced Neutron Production in Lead

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# Abstract

The COHERENT Collaboration is an experimental effort to make the first measurement of coherent elastic neutrino-nucleus scattering (CE $\nu$ NS). The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory provides an intense, timed source of neutrinos from the decay of pions and muons produced during the spallation of mercury by 1 GeV protons generated in a particle accelerator. COHERENT seeks to make an unambiguous measurement by using a variety of low-threshold detectors capable of measuring the low-energy nuclear recoils resulting from CE $\nu$ NS interactions [1]. This already challenging task is further complicated with the presence of backgrounds. Consequently, we must seek to reduce and understand our backgrounds as well as possible. A background measurement campaign of dedicated detectors has been deployed to study these backgrounds at the SNS. One such background is inelastic neutrino-nucleus neutron production, which produces nuclear recoils of similar energy and time structure as CE $\nu$ NS events. Inelastic neutrino-nucleus interactions are not well studied, and neutrino-induced neutron production has yet to be measured. Cross-sections predicted from nuclear theory are computationally impossible to be calculated exactly for large nuclei and differ by as much as 30% between different models [2] [3] [4]. The cross-section for neutrino-induced neutrons for large nuclei such as lead, an element commonly used in shielding material, is predicted to be comparable to the cross-section for CE $\nu$ NS. In addition to complimenting the detection of CE $\nu$ NS, this measurement is of interest to nuclear theory, supernova neutrino interactions and detection [5], and understanding backgrounds for all neutrino experiments at the SNS. Currently there are two detector modules containing lead and iron targets located 20 meters from the SNS neutrino source equipped with liquid scintillator cells for the detection of neutrino induced neutrons.

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# List of Abbreviations

ADC – Analog-to-Digital Conversion

BDT – Boosted Decision Tree

BRN – Beam Related Neutron

CE $\nu$ NS – Coherent Elastic Neutrino-Nucleus Scattering

CFD – Constant Fraction Discriminator

CMA – Conditional Moving Average (Filter)

DAQ – Data Acquisition

DIF – Decay-in-Flight

DIO – Decay in Orbit

DUNE – Deep Underground Neutrino Experiment

HALO – Helium and Lead Observatory

HARP – Hadron Production Experiment

IMB – Irvine-Michigan-Brookhaven (Detector)

LINAC – Linear Accelerator

LMA(-D) – Large Mixing Angle (Dark)

MARLEY – Model of Argon Reaction Low Energy Yields

MSW – Mikheyev-Smirnov-Wolfenstein

NIN – Neutrino Induced Neutron

NO/IO – Normal Ordering / Inverted Ordering

ORNL – Oak Ridge National Laboratory

(Pb)Nube – (Lead) Neutrino Cube

$\pi$ DAR – Pion Decay-at-Rest

PMT – Photomultiplier Tube

PSD – Pulse Shape Discrimination

SNEWS – Supernova Early Warning System

SM – Standard Model

SNS – Spallation Neutron Source

SN $\nu$  – Supernova Neutrino(s)

SNOLAB – Sudbury Neutrino Observatory Laboratory

TOF – Time of Flight

TUNL – Triangle University National Laboratory

$\nu$ N – Neutrino-Nucleus

# Chapter 1

## Introduction

Neutrino interactions with nuclei provide a different probe of nuclear structure by merit of their neutral electrical charge. As they only interact through the weak force, neutrino experiments are more difficult to perform and require low backgrounds and detectors sensitive to low-energy signal. The Spallation Neutron Source located at Oak Ridge National Laboratory in East Tennessee provides an intense, pulsed source of neutrinos. It is here that the COHERENT experiment has deployed an array of detectors using multiple nuclear targets, Cesium Iodide, Argon, Sodium Iodide, and eventually Germanium, designed to detect the small nuclear recoil resulting from the tiny kick the nucleus receives from a neutral current interaction with a neutrino. In addition to CE $\nu$ NS (coherent elastic neutrino-nucleus scattering) detection, there is a campaign to measure the various sources of backgrounds to reduce the systematic error of CE $\nu$ NS measurement. As a part of the background campaign, the Lead Neutrino-Induced Neutron Detector was deployed in early 2016 for the measurement of inelastic neutrino-nucleus scattering off lead, a commonly used shielding material. This process has yet to be measured by experiment and theoretical predictions have large uncertainty [2] [6]. This dissertation will review the present experimental efforts of COHERENT and focus on the simulation using GEANT4 Monte Carlo simulation package [7] and data analysis of beam-related-backgrounds and neutrino-induced neutrons seen in the Lead Neutrino-Induced Neutron Detector. Though a background for the detection of coherent elastic neutrino-nucleus scattering, inelastic neutrino-nucleus interactions are of interest themselves as a probe of nuclear structure and have yet to be experimentally measured for lead as well as other heavy nuclei. Such a measurement can provide information which can be used to constrain nuclear models which use empirical data to predict the effect of this process in heavy nuclei. Neutrino-induced neutron production in lead is also being used as a method of detecting supernova neutrinos for the HALO experiment and this measurement serves to increase the accuracy of SNO flux measurements from NIN events seen by the HALO detector [5].

# Chapter 2

## History of Neutrino Physics

In his letter in 1930, Wolfgang Pauli proposed a neutral, weakly interacting fermion to resolve energy and momentum conservation in  $\beta$ -decay with a mass on the same order of an electron. At the time,  $\beta$ -decay was thought to be a two-body decay which would result in monoenergetic decay products, but a continuous spectrum was observed as though the energy and momentum was shared by a third, undetected particle. Three years later in 1933, Perrin and Fermi both concluded this particle could be massless. “Fermi’s Interaction” is a description of  $\beta$ -decay that involves all four participating particles interacting at a single vertex. This precursor to the modern theory of weak interactions, which is mediated by the exchange of a virtual W boson, was very successful. At the time, the neutron had only just been recently discovered as a new kind of radiation by James Chadwick (1932) [8]. The radiation resulting by exposing Beryllium to alpha particles from a Polonium source was thought to be neutral, based on its highly penetrating nature. When exposed to a paraffin wax target, high energy protons were produced, ruling out the possibility of photons which lack the mass necessary to produce such results. Therefore, the radiation must be something previously undiscovered, neutrally charged, and with a mass close to that of the proton. The nucleus was previously thought to be comprised of protons and electrons in a bound state and the discovery of this new fundamental (thought to be fundamental, prior to the discovery of quarks) particle was a puzzling development. How could the positively charged nucleus remain bound by electromagnetic force alone?

Soon after the discovery of the neutron, efforts were made to understand this new nuclear force, led by Heisenberg. Yukawa predicted the existence of massive bosons participating as the exchange particle for the nuclear force with masses on the order of 100 MeV (hence *meson* from the Greek word *mesos* meaning ‘intermediate’). Lacking modern accelerators to search for this hypothesized particle, searches began with cosmic rays which were established to be high-energy particle cascades. The existence of the muon (initially dubbed *mesotron*) was established by cosmic ray observations and was initially thought to be Yukawa’s predicted particle, the  $\pi$ -

meson, because of its measured mass ( $\sim 100$  MeV) being similar to prediction. This particle was observed to have negative charge and to curved less sharply than the electron but more than the proton in a magnetic field at the same velocity. The difference in curvature was attributed to the difference in mass. Through experiment, the muon was ruled out as a candidate for mediating the nuclear force. The 1947 discovery of the  $\pi$ -meson from further cosmic ray studies using photographic emulsion plates definitively distinguished these two particles [9]. Charged particles passing through silver-gelatin emulsion plates leave tiny visible tracks. Charged  $\pi$ -mesons were characterized by their “double-meson” tracks (Figure 1), in which the  $\pi$ -meson decayed into a “mu-meson.” This distinction, along with observing that “mu-meson” did not participate in the nuclear force, lead to them being reclassified into a new family of particles along with the electron and neutrinos as leptons.

Similar to the  $\beta$ -decay spectrum, the muon decay spectrum was also observed to be continuous, implying two neutral interacting particles, neutrinos, were also present. Observations of muon decays were consistent with Fermi’s description of weak interactions and implied the universality of “Fermi Interactions” among leptons. This lead Pontecorvo to suggest a search for the direct detection of a neutrino through inverse  $\beta$ -decay,  $\bar{\nu}_e + p \rightarrow e^+ + n$ . The first direct detection of an electron anti-neutrino was the Cowan-Reines (1956) experiment, in which electron anti-neutrinos produced in a nuclear reactor were detected by the charged-current reaction on a proton in water target, producing a positron and a neutron [10]. The signal produced by this event was the prompt, back-to-back 511 keV photons detected in sheets of liquid scintillators, followed by a delayed 2.2 MeV photon from the capture of the neutron on  $^{108}\text{Cd}$  in the form of  $\text{CdCl}_2$ , used for its high neutron capture cross-section, mixed into the water target (Figure 2).

At the time, parity was thought to be a conserved quantity, a symmetry of the universe. In cosmic ray studies, a problem known as the  $\theta$ - $\tau$  puzzle appeared to violate P-symmetry, leading physicists to question parity conservation. The intrinsic parity of a pion is  $P = -1$ . Charged kaons produced in cosmic rays could decay into either  $2\pi$  or  $3\pi$ : states of even and odd parity respectively.  $\theta$  and  $\tau$  were thought to be two different particles differentiated by their decay mode. Lee and Yang (1956) noted the evidence for parity conservation was lacking in all weak interactions studied in the past [11]. The Wu Experiment marks the first direct observation of

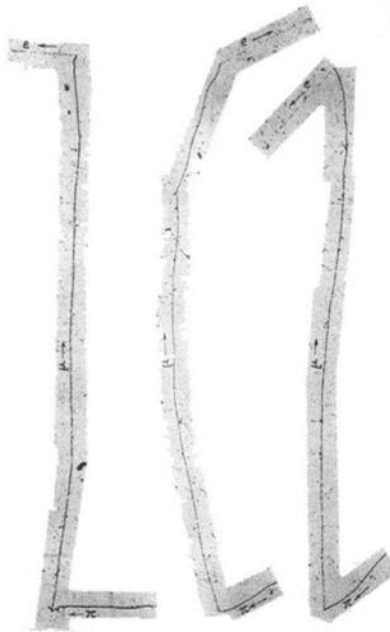


Figure 1. Photographic emulsion of charged particle tracks from cosmic rays. Each vertex is caused by a different decay. In this image, a charged pion decays into a muon, then the muon decays into an electron. The neutrinos participating in these decays leave no tracks, having no charge.

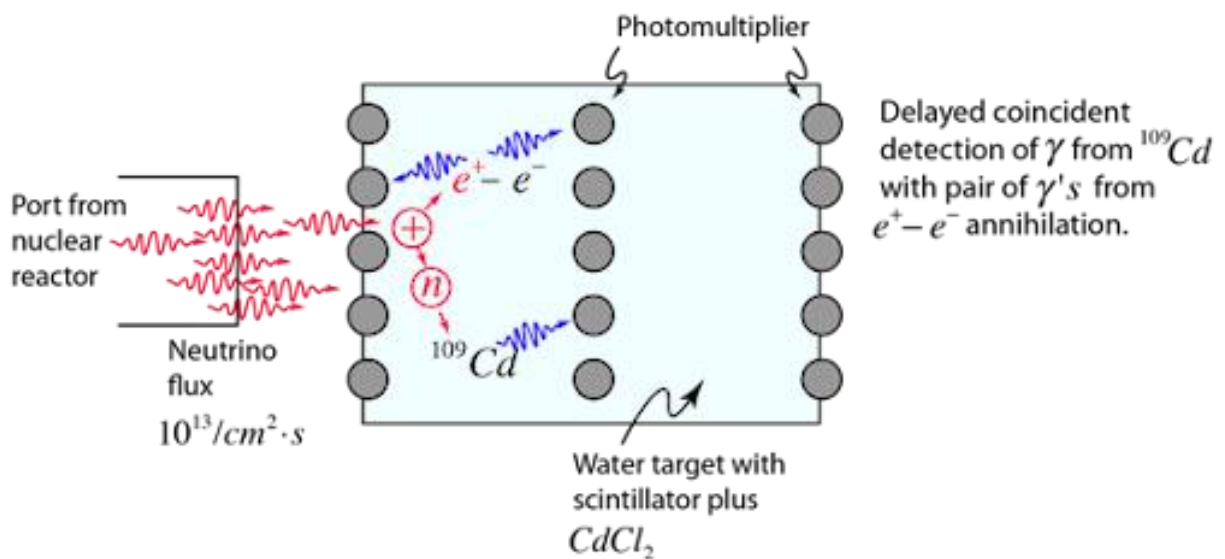
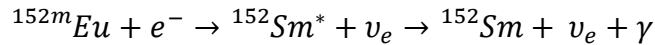


Figure 2. Schematic diagram of Cowan-Reines experiment. Anti-neutrinos (electron) produced from reactor  $\beta$ -decay interact with protons in water to produce a positron which would then pair-annihilate with electrons present in the water, producing back-to-back gammas accompanied by a delayed coincident signal from the capture of the neutron on  $^{108}\text{Cd}$ .

parity violation in weak interactions [12]. A solenoid magnetic field was used to align the nuclei of a  $^{60}\text{Co}$  sample, and the direction of the electron produced in the  $\beta$ -decay was measured with the reaction  $^{60}_{29}\text{Co} \rightarrow ^{60}_{28}\text{Ni}^* + e^- + \bar{\nu}_e$ . The  $^{60}\text{Co}$  nucleus has a spin of  $J = 5$  and the  $^{60}\text{Ni}$   $J = 4$ . Electrons and neutrinos, both fermions, have spin  $s = \pm 1/2$ . By conservation of angular momentum, the electron and neutrino, emitted opposite each other, conserve the difference of the nuclear spins. If parity was conserved, as it is in electromagnetic interactions, one would expect the electrons to be emitted ‘up’ and ‘down’ in equal number with respect to the nuclear spin. In a mirror-symmetric version of the experiment, the spins of the electron, neutrino, and  $^{60}\text{Co}$  nucleus are simply reversed relative to the direction the  $\beta$  is emitted. As a control, the direction of the photons from the decay of the excited  $^{60}\text{Ni}$ , a parity-obeying electromagnetic process, were observed to determine any possible lack of alignment of the sample. Wu observed an asymmetric number of events with electrons preferring to be emitted in the direction opposite to the direction of nuclear spin (Figure 3). The consequence of this being that the universe *does* have the ability to distinguish left from right.

Up until this point, there had been attempts to develop a theory of weak interactions which included parity conservation. Once parity violation was allowed, a new approach was needed to describe weak interactions and so V-A (vector-axial vector) theory was formulated by Feynmann, Gell-Mann, Sudarshan and Marshak in which weak interactions only act on left-handed particles and right-handed anti-particles. The ‘handedness’, or helicity, of the neutrino was experimentally confirmed in 1958 by counting photons emitted from the de-excitation of a  $^{152}\text{Eu}$  nucleus after electron K-shell capture using the reaction



with the possible spin state  $J: 0 \pm \frac{1}{2} \rightarrow \pm 1 \mp \frac{1}{2} \rightarrow 0 \mp \frac{1}{2} \pm 1$

Electromagnetic interactions conserve parity, therefore, the photon conserved the spin of the nucleus. Angular momentum conservation requires the nuclear spin to be opposite the spin of the neutrino. The experiment (Figure 4) was designed such that the photons were only detected if they were emitted opposite to the neutrino. The small shift in photon energy due to the nuclear recoil of the excited daughter nucleus  $^{152}\text{Sm}^*$  made nuclear resonance absorption possible on a nearby  $\text{Sm}_2\text{O}_3$  target only if the neutrino was emitted “up” and the photon was emitted opposite the neutrino. It was known that the cross-section of scattering depends strongly on the polarization of the scattering material. Magnetized blocks of iron were placed between the

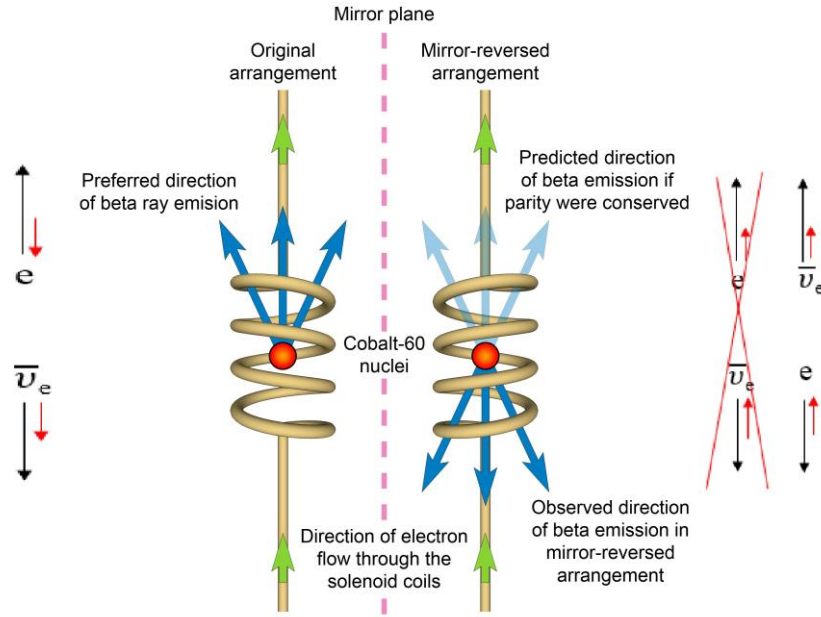


Figure 3. Depiction of Wu Experiment. Magnetically aligned sample of  $^{60}\text{Co}$  nuclei undergoing  $\beta$ -decay. If in weak interactions parity was conserved in weak interactions, the electrons would be emitted 'up' and 'down' in equal number. Black arrows indicate momentum direction and red indicates spin. The lack of 'up' electrons and 'down' neutrinos violate parity conservation.

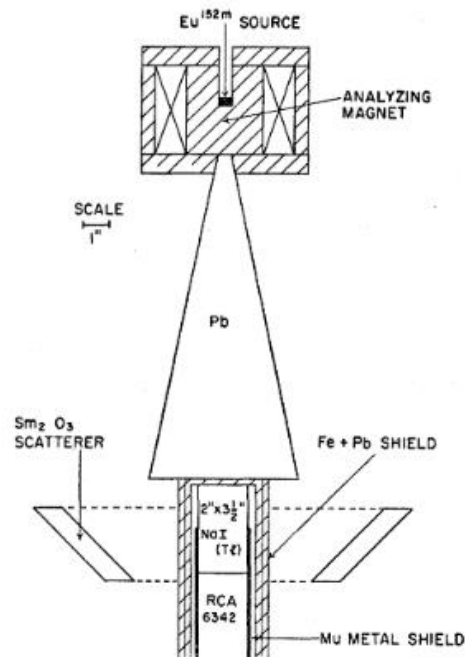


Figure 4. Experimental setup of Goldhaber experiment. When the field of the magnetized iron surrounding the source was aligned anti-aligned with the polarization of the emitted photon, photons could induce a spin-flip of the electrons in the iron and not when it the field is aligned. The asymmetry of counts from of both configurations was measured to determine the helicity of the neutrino.

source and the  $\text{Sm}_2\text{O}_3$  target. Photons which scattered in the iron and lost energy would lack sufficient energy for resonance scattering. In this experiment, if there were a preferred helicity of the photons, and by relation the neutrinos, there would be an observed asymmetry in count rates depending on the direction of polarization of the magnetized iron. This effect was observed by Goldhaber in 1958 [13]. This experiment demonstrated the helicity of the neutrino is  $H = -1$ : spin opposite the direction of momentum or “left-handed.” This also marked the first experimental confirmation of V-A theory.

The concept of Lepton Number Conservation had been proposed to explain the absence of reactions such as  $\bar{\nu}_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$ . Anti-neutrinos are assigned  $L = -1$  and neutrinos are assigned  $L = 1$ . Lepton Flavor Conservation was introduced to explain the suppression of  $\mu \rightarrow e + \gamma$ . It was hypothesized that if neutrinos produced from pion decay could not induce the reaction  $\nu_\mu + n \rightarrow p + \mu^-$  then the two neutrinos produced during muon decay were different particles. The existence of a second generation of neutrinos was established in 1962 in the first accelerator neutrino experiment, conducted at Brookhaven National Laboratory [14]. The accelerator produced 15 GeV protons, directed into a Beryllium target. The collisions produced various spallation products, but mostly pions. The beam of pions, muons, and neutrinos from decay-in-flight pions, mostly  $\pi^+$ , were directed into 13 meters of steel shield intended to stop everything except the neutrinos. Behind the steel shield was a large spark chamber of aluminum plates and neon gas, which observed the muon events resulting from the charged-current interaction of muon neutrinos on the aluminum plates, producing muons and not electrons, thus confirming two generations of neutrinos.

The previous decade of experiments yielded enough information to invite attempts to explain the relationship between known particles with a unified theory of electroweak interactions. Kaons in cosmic rays, the culprit of the  $\theta$ - $\tau$  puzzle, exhibited oddly long lifetimes, leading to the name of a new conserved quantity ‘strangeness’ or ‘S’. Also from cosmic rays, with an unexpectedly long lifetime, came the discovery of the Lambda particle, which decayed into a proton, unlike the kaon. The proliferation of elementary particles hinted at the possibility these were composite particles and not elementary and their lifetimes suggested some new mechanism governing their observed properties. The building blocks for the Standard Model of particle physics (SM) began to take their modern form with the development of Glashow’s

theory of electroweak interactions, predicting the existence of three massive gauge bosons, the  $W^\pm$  and  $Z^0$ , though the theory lacked renormalization [15]. Studies of weak interactions showed that the weak interactions involved vector-current couplings, implying the exchange of massive vector bosons. Massive bosons would violate the gauge invariance of a vector field in a Lagrangian. Contemporaneously, Gell-Man and Nishijima developed the eightfold way, the precursor to the quark model, as a classification system for observed particles using the SU(3) flavor symmetry of the up, down, and strange quark and their intrinsic spin and charge [16]. The composite nature of baryons was confirmed with deep inelastic scattering experiments performed at SLAC (1968) [17]. Weinberg incorporated the Higgs Mechanism into Glashow's electroweak theory, introducing spontaneous symmetry breaking, allowing the  $W^\pm$  and  $Z^0$  to be massive as they are in nature and providing a renormalizable theory [18]. The two-generation model was eventually extended to three after observing CP-violation that could be explained with an additional generation of quarks.

The first major success of the Standard Model was affirmed in 1973 with the discovery of neutral-current neutrino interactions mediated by the  $Z^0$  boson in the Gargamelle experiment at the Super Proton Synchrotron collider in CERN. Hadrons accelerated at the SPS collided on a Beryllium target to produce pions and kaons which decayed into neutrinos. The detector was a large bubble chamber of liquid Freon ( $\text{CBrF}_3$ ), looking for either leptonic, or more commonly, hadronic events in which the neutrino produced a recoil in an electron or nucleon, creating ionizing tracks in the liquid [19]. Overcoming the large experimental background of neutrons produced from inelastic neutrino-nucleus interactions in surrounding material, which mimic the nuclear recoils of neutral current interactions, this was an experimental success and confirmed the existence of the Z boson mediating these neutral current interactions. A few years after direct observation of the  $W^\pm$  and  $Z^0$  boson, the existence of a third generation of leptons was confirmed with the discovery of the tauon in 1975 at the Stanford Linear Accelerator Center as the only explanation for anomalous events from the reaction  $e^+ + e^- \rightarrow e^\pm + \mu^\mp + ?$  [20]. To conserve momentum and energy in the absence of any additional electrons, muons, photons, or hadrons the unknown was proposed to be a result of the decay of new particle-antiparticle pair  $\tau^+ + \tau^- \rightarrow e^\pm + \mu^\mp + 4\nu$ . It was logical to hypothesize an accompanying third tau neutrino. The number of generations was later fixed at three from measurements of the decay width of  $Z^0$  bosons produced at the Large Electron-Positron Collider in 1983 by the UA1 [21] and UA2 [22]

(Figure 5). At this point, the Standard Model picture was nearly complete apart from direct observation of the Higgs particle,  $\nu_\tau$ , and the top quark: all of which have at the present been confirmed through experimental observation (Figure 6).

However successful the Standard Model has been proven by experiment, there are definitive hints that the Standard Model is an incomplete theory with new physics lurking just beyond the Standard Model. One such phenomena is the observation of neutrino oscillations. The Homestake experiment led by Raymond Davis and John Bahcall was designed to detect charged current reactions of neutrinos produced from nuclear fusion in the Sun. The detector, a tank of perchloroethylene located deep underground to minimize the background of cosmic ray interactions. Electron neutrinos produced from fusion in the Sun interact with chlorine in the detector to produce  $^{37}\text{Ar}$ , which was collected by bubbling helium gas through the chamber. The experiment saw only a third of the expected number of events based on theoretical calculations done by Bahcall for the expected flux of neutrinos based on the Sun's luminosity. This anomaly was dubbed "The Solar Neutrino Problem" [23]. Inspired by observations of CP-violating oscillation of  $\bar{K}^0 \leftrightarrow K^0$ , Pontecorvo had already proposed the possibility of neutrino oscillations, but in the context of neutrino to anti-neutrino oscillation [24]. This idea lead Maki, Nakagawa, and Sakata to formulate a theory of neutrino flavor mixing [25], later expanded upon by Pontecorvo in 1967 [26], to provide the theoretical framework behind the PMNS matrix, the leptonic equivalent to the CKM quark-mixing matrix.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad (2.1)$$

The nine independent parameters above, which relate the neutrino mass eigenstates to their flavor eigenstates, can be reduced to just four:  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$ , and  $\delta_{\text{CP}}$  a CP-violating phase, in the following way where 's' and 'c' denote sine and cosine of these mixing angles between mass eigenstates. In the case that neutrinos behave as Majorana fermions in nature (as their own anti-particle), two additional phases,  $\eta_1$  and  $\eta_2$ , appear in the last term ( $\eta_1 = \eta_2 = 0$  for Dirac fermions).

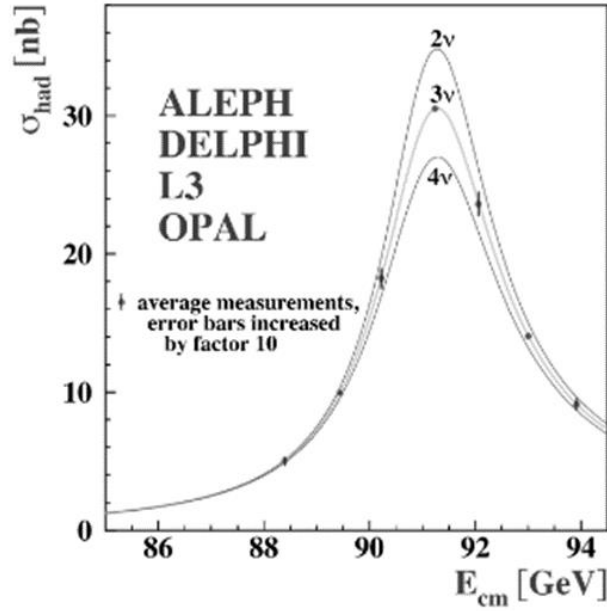


Figure 5. Z boson decay width from  $e^+e^-$  collisions at LEP. Shown curves are Standard Model predictions for width hadronic cross-section as function of center-of-mass energy for different number of light neutrino species. Additional neutrinos provide more decay possibilities for the Z boson, decreasing the hadronic cross-section. Experimental data indicates that three species is favored.

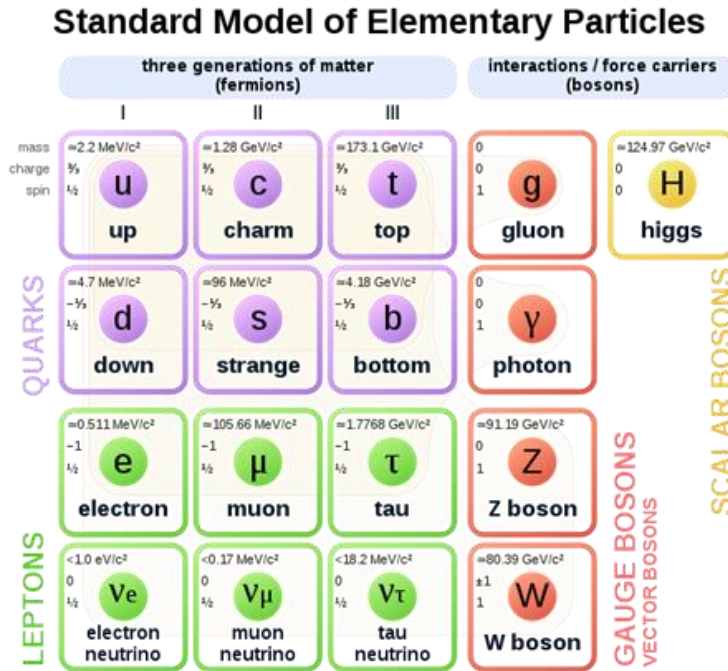


Figure 6. Presently known fundamental particles and their subclassification.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{23} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2.2)$$

In neutrino flavor mixing, neutrinos produced in a flavor eigenstate propagate in mass eigenstates that are a superposition of flavor eigenstates.

$$|v_\alpha\rangle = \sum_{i=1}^n U_{\alpha i}^* |v_i\rangle \quad (2.3)$$

Then the probability to find a neutrino of flavor  $\alpha$  ( $\alpha = e, \mu, \tau$ ) in another flavor state  $\beta$  is given as

$$P_{\alpha\beta} = |\langle v_\beta | v_\alpha \rangle|^2 = \left| \sum_{i=1}^n \sum_{j=1}^n U_{\alpha i}^* U_{\beta j} \langle v_j | v_i(t) \rangle \right|^2 \quad (2.4)$$

Considering  $|v\rangle$  to be a time-dependent wavefunction of the form  $|v_i(t)\rangle = e^{-iE_i t} |v_i(0)\rangle$  and light neutrinos to be almost always relativistic such that  $E \cong p$ ,  $P_{\alpha\beta}$  becomes

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i<j}^n \text{Re} [U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}] \sin^2 X_{ij} + 2 \sum_{i<j}^n \text{Im} [U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}] \sin 2X_{ij} \quad (2.5)$$

where  $X_{ij} = (m_i^2 - m_j^2)L/2E$ . After traveling some distance  $L$ , a neutrino of energy  $E$  produced in one flavor state has a finite, periodic probability to be found in another flavor state depending on mixing angles, mass-squared difference, and  $L/E$ : an important parameter of oscillation experiments [27]. When the ‘‘Solar Neutrino Problem’’ was observed, neutrino oscillation seemed a natural explanation. In the Standard Model, neutrinos are massless, but to oscillate between flavor states, neutrinos need to have mass. Therefore, neutrinos must somehow acquire their tiny masses through physics beyond the Standard Model.

The simplest extension of the SM to provide neutrinos with masses is to include a right-handed component of the neutrinos. Active neutrinos are left-handed in SM, but mass terms of SM particles involve coupling of left and right fields and are of the form:

$$-\mathcal{L}_m = m \bar{\varphi} \varphi = \overline{(\varphi_L + \varphi_R)} (\varphi_L + \varphi_R) = \bar{\varphi}_L \varphi_R + \bar{\varphi}_R \varphi_L \quad (2.6)$$

There are two possible cases, the first is if the left and right components are independent, making them Dirac fermions. The second is if the right-handed component is the anti-particle conjugate of the left,  $\varphi_L = (\varphi^c)_R$ , or Majorana fermions. The mass terms become

$$-\mathcal{L}_m = m_{LR}\bar{u}_L u_R + m_{LR}\bar{u}_R^c u_L^c + m_{RR}\bar{u}_R^c u_R = (\bar{u}_L \ \bar{u}_R^c) \begin{pmatrix} 0 & m_{LR} \\ m_{LR} & m_{RR} \end{pmatrix} \begin{pmatrix} u_L^c \\ u_R \end{pmatrix} \quad (2.7)$$

where  $m_{LR} = Y_\nu \frac{v}{\sqrt{2}}$  and comes from spontaneous symmetry breaking. In the case of purely Dirac neutrinos, only  $m_{LR}$  remains but does not provide an immediate explanation for the smallness of neutrino masses. Initially,  $m_{LL} = 0$ . Diagonalizing the matrix in Equation 2.7 yields the mass eigenvalues:

$$m_\pm = \frac{m_{RR} \pm \sqrt{m_{RR}^2 + 4m_{LR}^2}}{2} \text{ and } m_{LL} = \frac{m_{LR}^2}{m_{RR}} \quad (2.8)$$

The resulting mass eigenstates are an admixture of the Dirac and Majorana masses. Active, left-handed neutrinos are light with a very small contribution from the right-handed, heavy states and the sterile, right-handed neutrinos are heavy. Hence the name ‘‘See-Saw Mechanism’’ (Figure 7). It is assumed that  $m_{RR} \gg m_{LR}$  with  $m_{RR}$  being on the order of Grand Unification Theory (GUT) scale where accidental SM symmetries such as Lepton Number Conservation may no longer hold. Without the inclusion of beyond Standard Model, higher-dimensional operators, right-handed heavy Majorana mass states are required to explain the smallness of neutrino masses relative to other particles. If this is true, processes like neutrino-less double-beta decay will be observable.

Since the observation of the ‘‘Solar Neutrino Problem,’’ extensive experimental effort has been dedicated to understanding this phenomenon. Experimental confirmation for disappearance of solar  $\nu_e$  neutrinos was achieved by a joint effort of two large scale water Cherenkov detectors (Figure 8): Super-Kamiokande [28] and Sudbury Neutrino Observatory [29] (SNOLAB). Both facilities are located deep underground to minimize background in search of neutrino events. The Standard Solar Model (SSM) predicts the Sun’s neutrino luminosity based on a fusion chain model. Most neutrinos produced are from proton-proton reactions and are too low in energy ( $< 1$  MeV) to be easily detected. However,  $\nu_e$  from the reaction  ${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$  in the solar fusion chain have energy up to 15 MeV and are more easily detected. SNOLAB’s heavy-water detector searched for  ${}^8\text{B}$  neutrinos using three methods of detection: elastic-scattering of electrons, charged-current  $\nu_e + D \rightarrow e^- + p + n$ , and neutral-current  $\nu_l + D \rightarrow \nu_l + p + p$  which is sensitive to all three flavors. From comparison of the different signals, there is a clear indication of  $\nu_e \rightarrow \nu_{\mu,\tau}$  oscillation and consequent confirmation of the Solar Standard Model

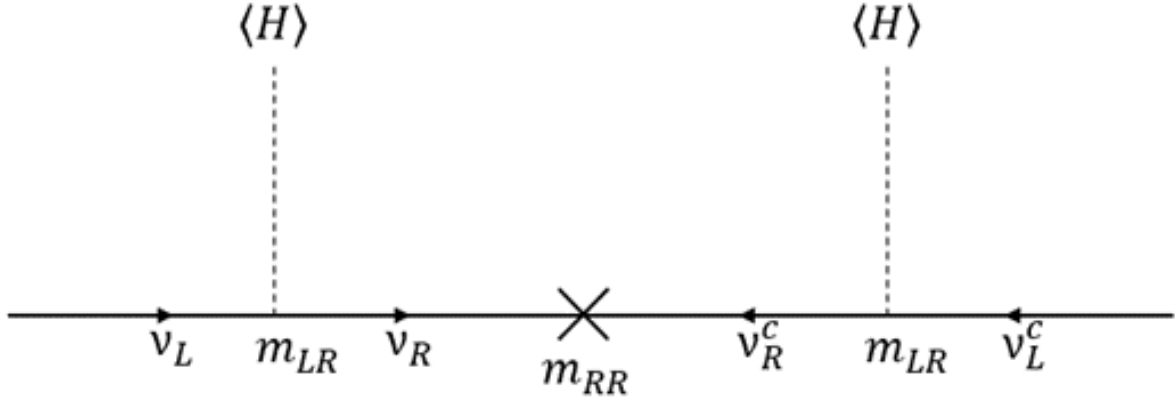


Figure 7. Diagram of “See-Saw” Mechanism for neutrino masses.

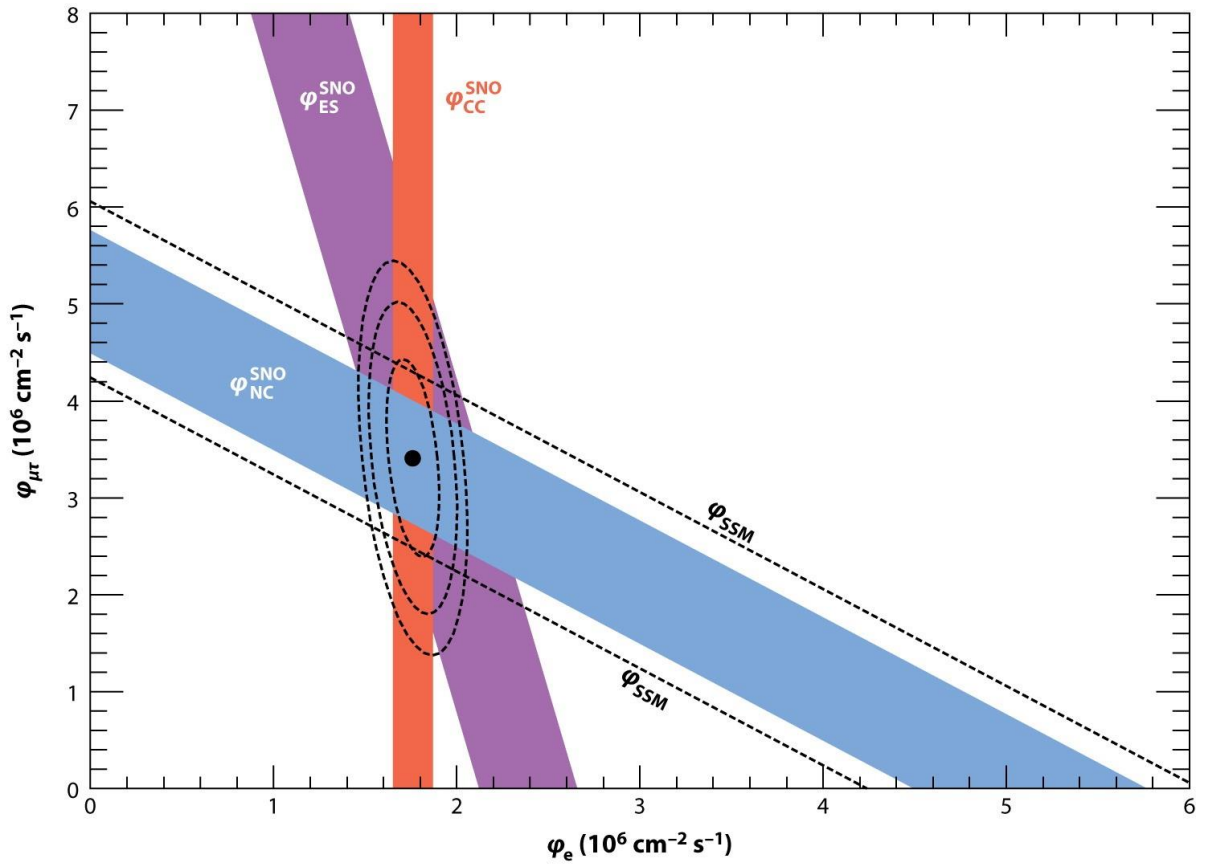


Figure 8. SNOLAB cross-plot of  $^8\text{B}$  solar neutrino flux combined with Super-Kamiokande elastic scattering data with  $1\text{-}3\sigma$  of best-fit from [29].

called the large mixing angle (LMA) MSW solution. The MSW (Mikheyev-Smirnov-Wolfenstein) effect accounts for matter-influenced oscillation as neutrinos propagate through dense stellar material. The combination of SNOLAB's solar neutrino data with KamLAND's reactor neutrino data results in mixing parameters of  $\Delta m_{\odot}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$  and  $\sin^2 \theta \sim 0.3$ .

Water Cherenkov Super-Kamiokande neutrino detector looks for the Cherenkov light produced from relativistic charged particles produced in charged-current neutrino interactions. Electrons create a diffuse ring of light whereas muons create a sharp ring which is seen by a large array of phototubes surrounding the target volume, which allows for event identification as well as determination of the directionality of the incident neutrino. Super-Kamiokande, while also sensitive to elastic  $\nu$ -e scattering of  $^8\text{B}$  solar neutrinos, is also an atmospheric neutrino experiment. The particle shower from high energy particles interacting in upper atmosphere produce pions and kaons that decay into  $(\text{anti-})\nu_{e,\mu}$  that travel  $10$ - $10^4$  km depending on where in the atmosphere the neutrino originated. Considering the spherical nature of our planet, one can expect a spherical symmetry of atmospheric neutrinos with respect to zenith angle. Super-Kamiokande observed a disappearance of  $\nu_{\mu}$  for upward directed neutrinos (through the Earth, correlated with longer distance). The  $\nu_e$  events followed their symmetric flux prediction, implying the parameters of  $\Delta m^2$  and  $L/E$  for atmospheric  $\nu_e$  neutrinos are not sufficient to observe oscillation (Figure 9). SuperK's result for  $\nu_{\mu} \rightarrow \tau$  oscillation corresponds to oscillation parameters of  $\Delta m_{atm}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2$  and  $\theta \sim 45^\circ$ . SuperK also observed a day-night asymmetry of solar  $^8\text{B}$   $\nu_e$ , consistent with the MSW effect.

Nuclear reactors provide an abundant neutrino source with which to study flavor oscillation. Nuclear reactors produce electron anti-neutrinos with energy on the order a few MeV. Oscillation of reactor neutrinos to other flavor states cannot induce a charged-current reaction by inverse beta decay, lacking sufficient energy for muon or tau production. KamLAND (result in Fig. 10), a 1 kT liquid scintillator detector located an average of  $\sim 180$  km from several reactors, looks for reactor electron anti-neutrino disappearance by inverse beta decay [30]. KamLAND's location is sensitive to oscillations corresponding to  $\Delta m^2 \sim 10^{-4} - 10^{-5} \text{ eV}^2$ .

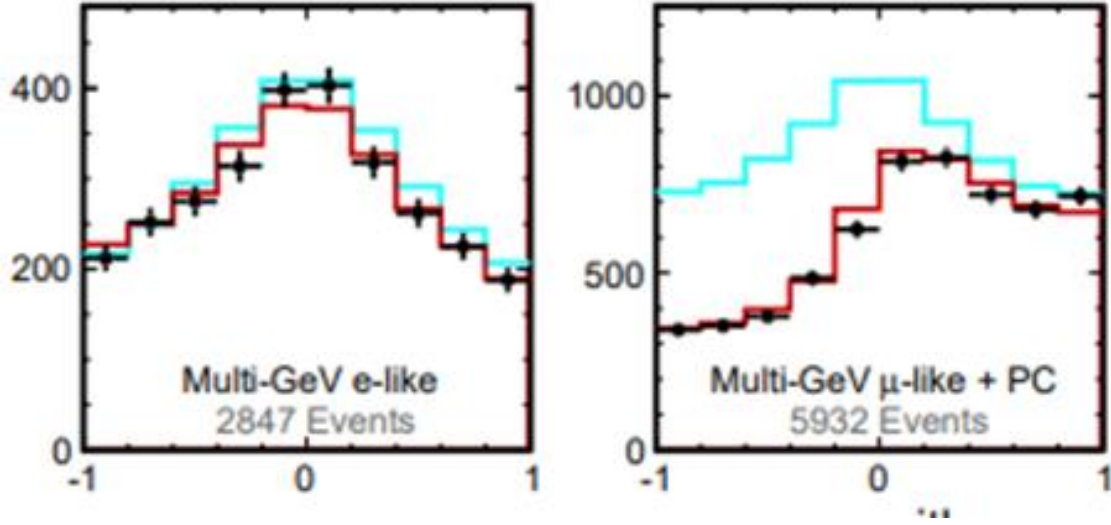


Figure 9. Atmospheric neutrino data from Super Kamiokande. Blue line is prediction for no oscillation and red is best fit for  $\nu_\mu \rightarrow \nu_\tau$  oscillation.

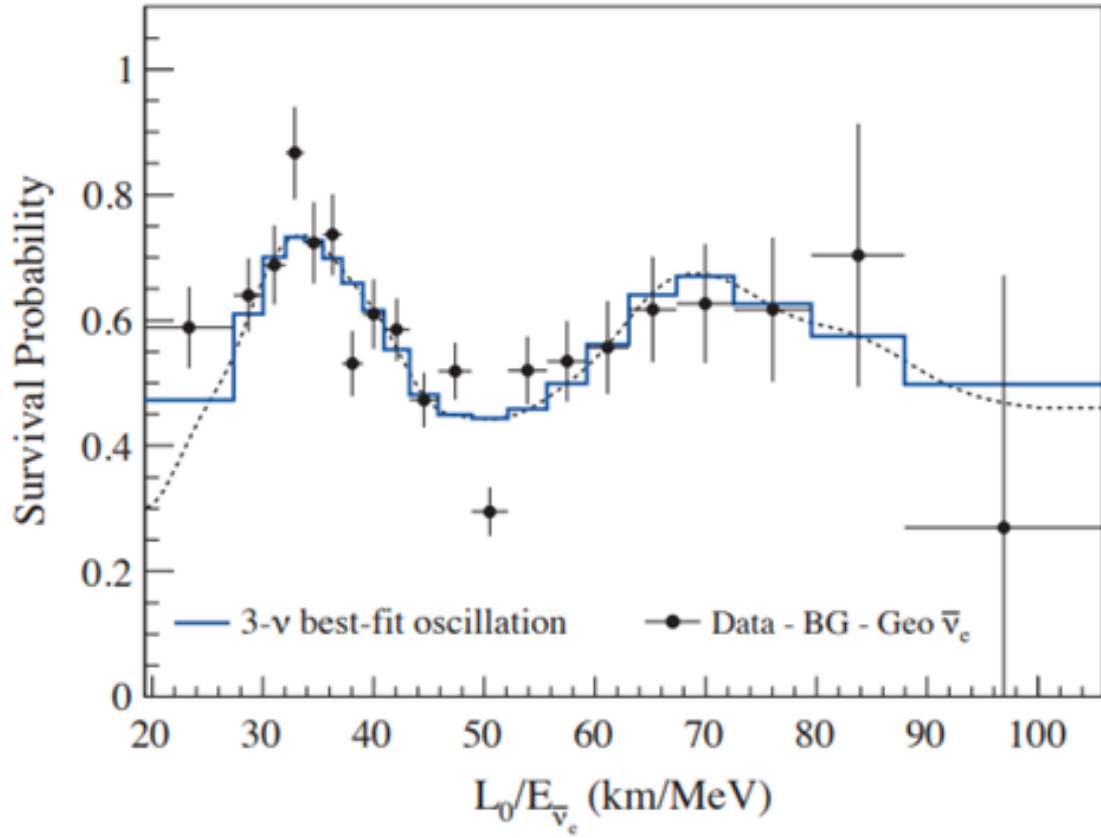


Figure 10. KamLAND data for reactor neutrino disappearance [27]. Best fit agrees with prediction of oscillatory pattern of  $L/E_\nu$ . KamLAND's results agree with the LMA MSW solution for solar neutrino data.

Other reactor experiments such as Double Chooz in France and Daya Bay in China have detectors near the reactor, on the order of 1 km corresponding to  $\Delta m^2 \sim 10^{-2} - 10^{-3} \text{ eV}^2$ , to make a precise measurement of  $\theta_{13}$ . There have been hints of oscillation at  $\Delta m^2 \sim 1 \text{ eV}^2$ , suggesting the possibility of light sterile states, for which short baseline ( $\sim 10 \text{ m}$ ) reactor neutrino experiments have been realized. However, in the broader picture of global data, models with additional light neutrinos have been excluded with large statistical significance.

Considering the form of Equation 2.5, the choice of source for oscillation experiment and therefore the distance and energy and corresponding to the sensitivity to mass difference and mixing angle. The number of parameters in 3 $\nu$  flavor mixing motivates the necessity of multiple experiments to accurately determine these. Accelerator neutrino experiment provide another avenue to explore with both long baseline and short baseline experiments, searching for either appearance or disappearance of neutrino flavors and scanning parameter space with different accelerator configurations. Proton beams produce short-lived mesons whose decay products include  $\nu_\mu$  and  $\nu_e$  (and their anti-partners), much like cosmic rays. The customizability for accelerator neutrino sources allows for precision measurement of mixing angles and the search of possible CP violation with comparison of  $\bar{\nu}_{e,\mu}$  and  $\nu_{e,\mu}$ . In summary, solar experiments provide information relevant to measurement of  $\theta_{12}$ ,  $\Delta m_{21}^2$ , and  $\theta_{13}$ . Long baseline reactor experiments are ideal for measuring  $\Delta m_{21}^2$ , while also providing information of  $\theta_{12}$  and  $\theta_{13}$ . Medium baseline reactor experiments ( $\sim 1 \text{ km}$ ) pick up the first oscillation peak of  $\Delta m_{32,31}^2$  and relevant mixing angle  $\theta_{13}$ . Atmospheric experiments are valuable for  $\theta_{23}$ ,  $\Delta m_{32,31}^2$ ,  $\theta_{13}$ ,  $\delta_{\text{CP}}$ . Accelerator experiments using both disappearance and appearance can be designed for precision measurement of  $\Delta m_{32,31}^2$ ,  $\theta_{23}$ ,  $\delta_{\text{CP}}$ , and  $\theta_{23}$ . The present status of global measurements is presented in Table 1.

However, neutrino oscillation data only informs values of the squared mass difference  $\Delta m_{ij}^2$  and not the absolute mass or the order of mass states (Figure 11). A dedicated experiment to determine the absolute mass can be theoretically accomplished by study of the endpoint of the  $\beta$ -decay spectrum. The presence of  $m_\nu \neq 0$  will create visible distortion to the electron energy spectrum. Presently, KATRIN [31], which uses the  $\beta$ -decay of tritium, has put the most stringent limit on  $m_{\nu_e}^{\text{eff}} \leq 1.1 \text{ eV}$ , which relates to the lightest neutrino mass state by:

Table 1. Global fit of neutrino oscillation data. Normal mass ordering ( $m_1 < m_2 < m_3$ ) is favored over inverted mass ordering ( $m_3 < m_1 < m_2$ ) by  $2.5\sigma$  [32].

| Parameter                                            | Best fit $\pm 1\sigma$    | $2\sigma$ range | $3\sigma$ range |
|------------------------------------------------------|---------------------------|-----------------|-----------------|
| $\Delta m_{21}^2: [10^{-5}\text{eV}^2]$              | $7.50^{+0.22}_{-0.20}$    | $7.11 - 7.93$   | $6.94 - 8.14$   |
| $ \Delta m_{31}^2 : [10^{-3}\text{eV}^2](\text{NO})$ | $2.55^{+0.02}_{-0.03}$    | $2.49 - 2.60$   | $2.47 - 2.63$   |
| $ \Delta m_{31}^2 : [10^{-3}\text{eV}^2](\text{IO})$ | $2.45^{+0.02}_{-0.03}$    | $2.39 - 2.50$   | $2.37 - 2.53$   |
| $\sin^2\theta_{12}/10^{-1}$                          | $3.18 \pm 0.16$           | $2.86 - 3.52$   | $2.71 - 3.69$   |
| $\sin^2\theta_{23}/10^{-1} (\text{NO})$              | $5.74 \pm 0.14$           | $5.41 - 5.99$   | $4.34 - 6.10$   |
| $\sin^2\theta_{23}/10^{-1} (\text{IO})$              | $5.78^{+0.10}_{-0.17}$    | $5.41 - 5.98$   | $4.33 - 6.08$   |
| $\sin^2\theta_{13}/10^{-2} (\text{NO})$              | $2.200^{+0.069}_{-0.062}$ | $2.069 - 2.337$ | $2.000 - 2.405$ |
| $\sin^2\theta_{13}/10^{-2} (\text{IO})$              | $2.225^{+0.690}_{-0.070}$ | $2.086 - 2.356$ | $2.018 - 2.424$ |
| $\delta_{CP}/\pi (\text{NO})$                        | $1.08^{+0.13}_{-0.12}$    | $0.84 - 1.42$   | $0.71 - 1.99$   |
| $\delta_{CP}/\pi (\text{IO})$                        | $1.58^{+0.15}_{-0.16}$    | $1.26 - 1.85$   | $1.11 - 1.96$   |

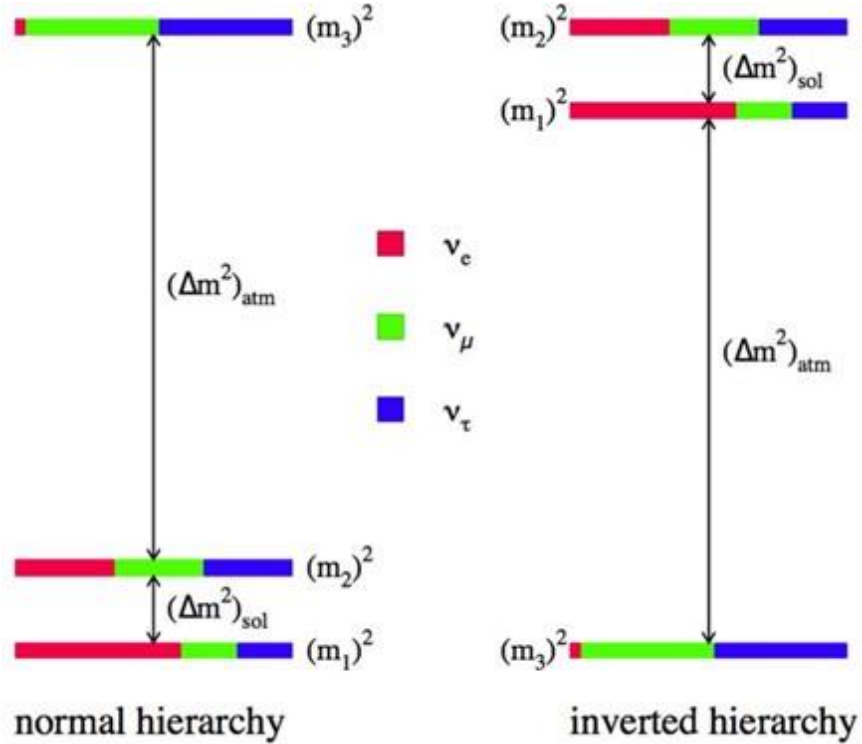


Figure 11. Neutrino mass hierarchy with relative flavor composition. Mass splitting from experiment cannot yet definitively distinguish between the two possible orderings.

$$m_{\nu_e}^{eff} = \sqrt{\sum_i m_i^2 |U_{ei}|^2} = \begin{cases} \sqrt{m_0^2 + \Delta m_{21}^2 (1 - c_{13}^2 c_{12}^2) + \Delta m_{32}^2 s_{23}^2} \\ \sqrt{m_0^2 + \Delta m_{21}^2 c_{13}^2 c_{12}^2 - \Delta m_{32}^2 c_{13}^2} \end{cases} \quad (2.9)$$

for normal ordering (NO) and inverted ordering (IO) respectively where  $m_0 = m_1(m_3)$  is the lightest neutrino mass. If the value of  $m_{\nu_e}$  is measured below a certain value, it would distinguish between normal or inverted mass hierarchy. Neutrino-less double beta decay experiments also have the potential to measure absolute mass and determine hierarchy (Figure 12), as the predicted rate for this process depends on the effective Majorana mass of  $\nu_e$ ,  $m_{ee}$ :

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \left( \frac{m_{ee}}{m_e} \right)^2 \quad (2.10)$$

where  $G^{0\nu}$  is the phase space integral of the final atomic state and  $|M^{0\nu}|$  is the nuclear matrix element of the process. There are 35 candidate nuclei for double beta decay, the most common being  $^{136}\text{Xe}$  and  $^{76}\text{Ge}$ , as with experiments such as liquid-xenon loaded scintillator KamLAND-Zen [33] and high-purity enriched Germanium for GERDA and Majorana, now LEGEND [34].

Presently, neutrino physics contains several compelling open questions with the potential for new physics beyond the Standard Model. Most of what we have learned about neutrinos from direct detection experiments comes from a humble number of events. Early in its theoretical beginnings, the neutrino was even hypothesized to be undetectable. As experiments are entering a precision era with modern technology, the answer to the remaining mysteries of neutrino physics may lie just beyond the horizon. Neutrinos present an interesting puzzle and have long existed as a fruitful avenue to beyond Standard Model physics and the complimentary interest of neutrino experiments for nuclear, particle, and astrophysics increase the importance of this frontier. For this reason, understanding the nature of neutrinos and their interactions with other matter has become a priority of contemporary physics with the next generation of neutrino experiments.

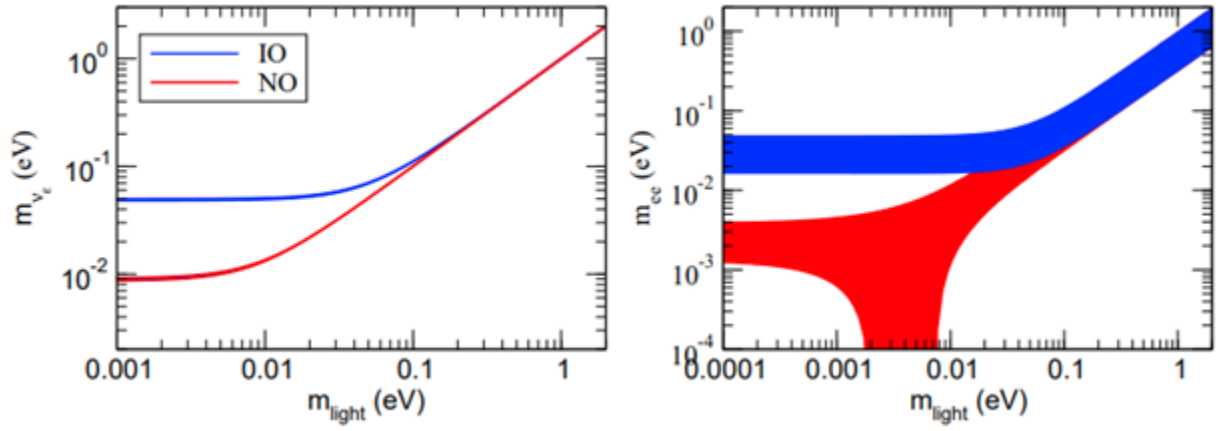


Figure 12. 95% confidence limits for observable neutrino mass as function of lightest mass state determined in the context of  $3\nu$  mixing from global oscillation data. Left is for beta decay and right is  $0\nu\beta\beta$ . The large range of values for  $0\nu\beta\beta$  is due to uncertainty of nuclear matrix elements and unknown Majorana phases.

# Chapter 3

## Neutrinos in Core-Collapse Supernovae

Neutrinos are produced and interact in nature via weak interactions. Nuclear reactions such as  $\beta$ -decay or fusion involve weak processes and produce neutrinos. Knowledge of this allows for predictions of neutrino production in nuclear reactors, our Sun, or even supernovae. Once neutrinos are produced, they are very unlikely to interact with matter in their path of propagation. The detection of neutrinos from these sources serves as an extra piece of information for theoretical models of the physics governing these neutrino sources. Additionally, by studying the interactions of neutrinos with nuclei and the nuclear transitions they can induce we gain experimental information to compare with predictions of different nuclear models.

Supernova 1987a marked the birth of supernova neutrino astrophysics. Neutrinos produced from this supernova in the neighboring galaxy Large Magellanic Cloud were detected in earthbound neutrino detectors [35]. Twenty-five electron anti-neutrino events in total were detected above background roughly in coincidence, but with some spread in time by Kamiokande, Irvine-Michigan-Brookhaven detector (IMB), and the Baksan Neutrino Observatory. Despite limited statistics, analysis yielded an upper bound on the neutrino mass of 16 eV and a maximum number of neutrino flavors of eight. Since the compact proto-neutron star in a core collapse supernova becomes transparent to the weakly-interacting neutrinos before photons can escape the surface of the star, the neutrinos, which travel at nearly the speed of light, will precede the light output from the supernova, making them a convenient early warning signal for telescopes waiting to observe the impending electromagnetic radiation. For this purpose, a network of neutrino detectors around the world have coordinated to search for a simultaneous signal from the burst of neutrinos associated with a core-collapse supernova.

In addition to studying the light output of supernovas, the neutrino signature provides additional insight towards the mechanisms driving core-collapse supernova. The energy and flavor-content of neutrinos produced during these events depends on the astrophysical conditions where they are produced. Unfortunately, at the energies at which these neutrinos are produced,

the only charged-current events that will occur will be of the electron type. Neutral-current events are flavor blind, making it difficult to constrain the relative spectra of neutrino flavors. Additionally, the relative flavor abundances will be obscured by oscillations through variable distances of both dense stellar material and vacuum. This is further complicated by the possibility of collective oscillations with neutrino self-interactions.

It is known from simulation and theory that neutrinos play an integral role in the kinematics of core-collapse supernova. Once a star has depleted its nuclear energy source, the core grows unstable against its own gravity. The electrons in the core provide the outward pressure and the electron Fermi energy grows as the degenerate sea of electrons is compressed. The core can efficiently lower its free energy by electron capture on protons. At densities of  $\rho < 10^{11} \text{ g/cm}^3$ , neutrinos produced from electron capture and  $\beta$ -decay can leave the star, reducing the entropy and free energy [36]. Consequently, heavy nuclei do not escape the collapse. Electron capture dominates and the electron degeneracy pressure decreases, accelerating the collapse. The core material becomes increasingly neutron rich. Nuclei that are unstable against  $\beta$ -decay are unable to decay due to Pauli blocking of phase-space by the highly degenerate electron gas. As the density grows in excess of  $\rho > 10^{11} \text{ g/cm}^3$ ,  $\beta$ -decay is entirely Pauli blocked and only electron capture can occur.

As core density grows in excess of  $\rho > 4 * 10^{11} \text{ g/cm}^3$ , neutrinos become trapped. The dominant process is coherent neutrino-nucleus elastic scattering as neutrinos produced in supernova have typical energies of less than 50 MeV and the mean free path for a neutrino is about 0.5 km, less than the radius of the stellar core [37]. Their propagation can be described as a diffusive process, with the timescale of their diffusion being greater than the timescale of the collapse. Neutrinos can also exchange energy with core material via inelastic scattering. Supernova conditions have finite temperature effects, namely the populating of excited nuclear states. This allows for neutrinos to both down-scatter and up-scatter off nuclei. Neutrino-electron scattering is much more likely though and efficiently thermalizes the neutrinos with the surrounding matter, as it can only down-scatter from the highly degenerate electrons. Figure 13 illustrates the evolution of these processes and the correlated neutrino interactions.

After neutrino trapping, the collapse proceeds until nuclear density is reached. Nuclear material is much less compressible, halting the collapse. The core “bounce” drives a shockwave

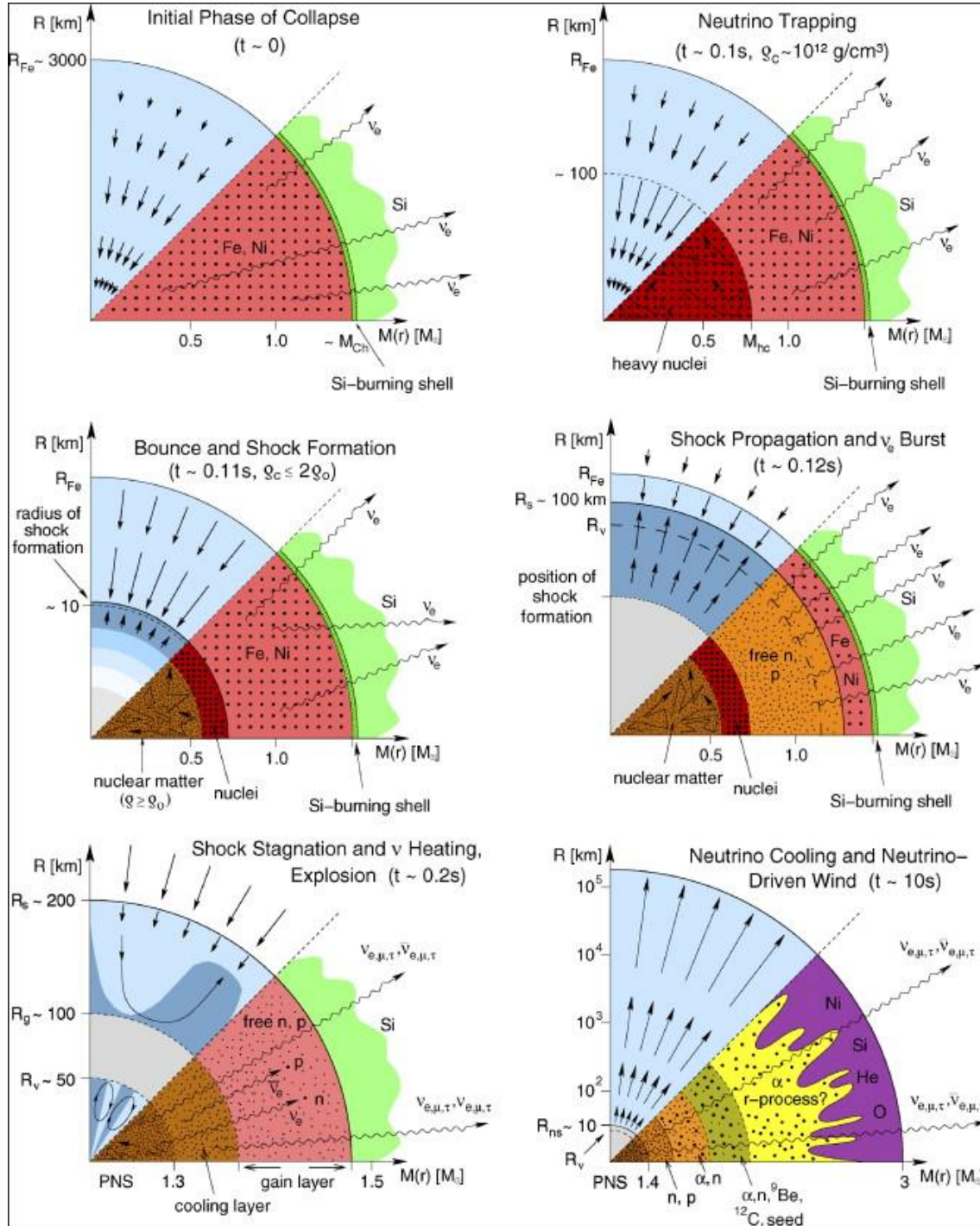


Figure 13. Schematic of evolution of neutrinos and their interactions with stellar material [38]. The upper portion of each diagram shows the motion of material with arrows indicating velocity vectors.  $M_{Ch}$  represents Chandrasekhar mass,  $M_{hc}$  is the homogeneously collapsing core.  $R_{Fe}$ ,  $R_s$ ,  $R_G$ ,  $R_{NS}$ , and  $R_\nu$  are the radii of the iron core, shock front, gain radius, neutron star, and neutrinosphere.

into the still collapsing outer core. The in-falling material is dissociated into protons and neutrons, using up the energy of the shockwave and eventually stalling the shock front. Electrons capture on free protons in the layers of material between the proto-neutron star and stalled shock front, increasing the number of neutrons to be quickly captured by neutron deficient nuclei [37]. Neutrinos produced from the electron captures behind the shock front are free-streaming and leave the star, carrying away energy. This luminous event is known as the neutrino burst at shock break out, after which the neutrino luminosity decreases (Figure 14).

After the core bounce, a compact remnant is left behind which will either collapse into a black hole or become a neutron star depending on the mass of the progenitor star. In the case of a neutron star, trapped neutrinos begin to diffuse out, thermalizing their initially high degeneracy energy with the stellar medium [39]. The proto-neutron star begins to cool via pair production and related processes of all three neutrino flavors. After tens of seconds, the entire star becomes transparent to neutrinos and the luminosity drops significantly. Neutrinos carry away 99% of the kinetic energy released during a core-collapse event, so it is nearly redundant to say they drive the kinematics of the explosion. In a process called the “delayed neutrino heating mechanism,” energy carried away from the proto-neutron star by neutrinos can be deposited in the material between the star and the stalled shock front, heating the material [40]. The dominant process is neutrino capture on nucleons. Neutrons produced at these sites are quickly captured by nuclei, so there are mostly free protons and nuclei available. This is where the more recently discovered nucleosynthesis process called the “vp-process” takes place. The “vp-process” is thought to be responsible for the formation of rarer isotopes of medium-heavy mass elements and is made possible by charged-current neutrino interactions (Figure 15) [41].

The deposition of energy from neutrinos is necessary to revive the stalled shock front. In spherically asymmetric supernova models, the neutrino wind coming from the cooling proto-neutron star creates regions of low density and high temperature which cause convective flows of stellar material. This process increases the amount of time matter spends in these high neutrino flux environments and increases the energy deposited by the neutrino wind. This “hot neutrino bubble” produced by neutrino winds is the favored candidate for reviving the explosion in core-

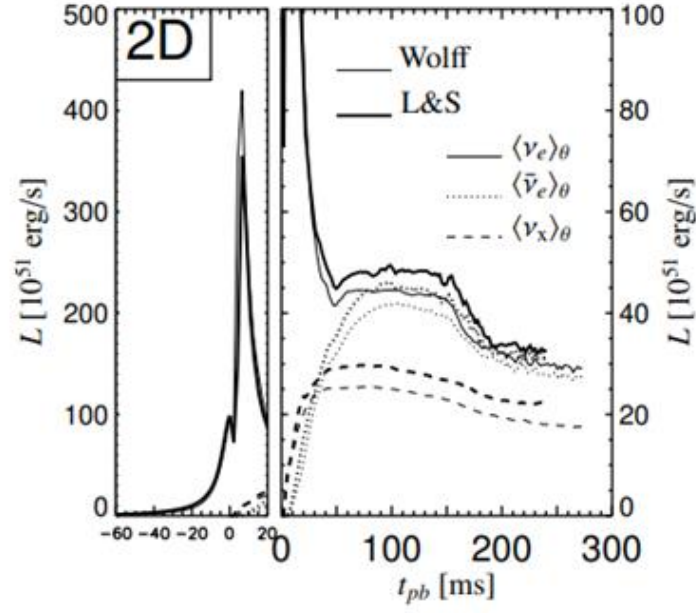


Figure 14. 2-D simulation results of neutrino luminosity vs time during core-collapse supernova using equations of states from Wolfe [42] and Lattimer & Swesty [43] for a  $15 M_{\odot}$  progenitor star. Left panel shows prompt  $\nu_e$  burst and right is post-bounce luminosity of (anti) $\nu_e$  and heavy-lepton flavor  $\nu_x$ . (from [38]).

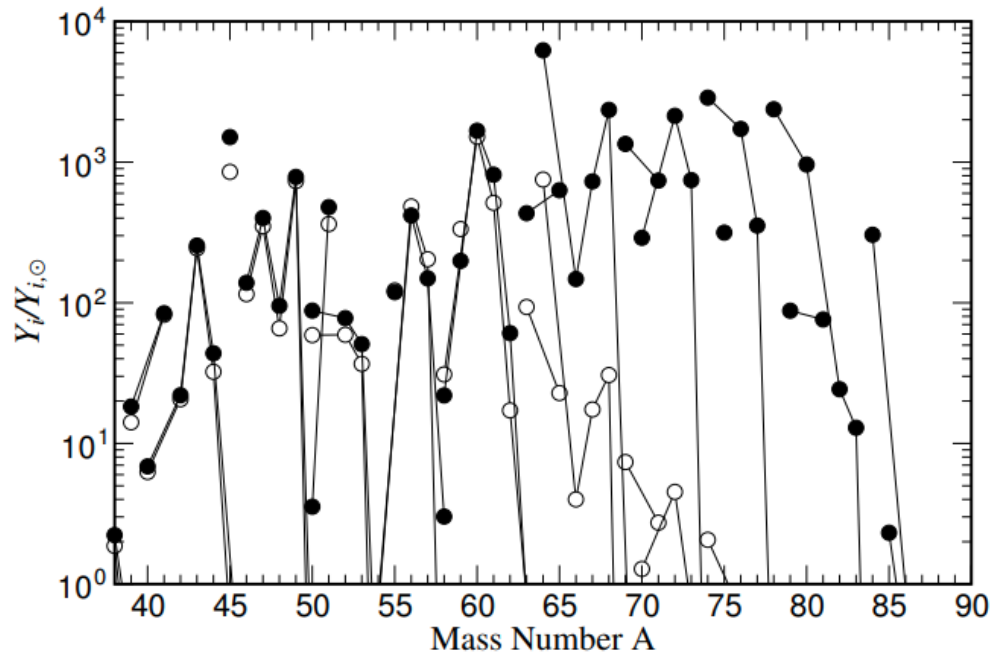


Figure 15. Isotopic abundances relative to solar abundances resulting from supernova  $\nu p$ -process nucleosynthesis obtained from [41]. Calculations including include (anti)neutrino absorption are represented by and open spheres where calculations neglect (anti)neutrino absorption.

collapse supernova [44]. Although there are nuclei present throughout a core-collapse supernova event, the photodisintegration of nuclei into free nucleons and alpha particles in the neutrino heated matter indicate that nuclei do not play a large role in the kinematics of the explosion. Neutrino interactions with nucleons and electrons have much greater effect on the resulting neutrino energy spectra and powering the explosion. Neutrino-induced nucleus interactions may be the nucleosynthesis process behind the production of certain isotopes  $^{11}\text{B}$  or  $^{19}\text{F}$  at locations far from the star and can occur from either neutral or charged-current interactions, therefore the abundances would be sensitive to both  $\nu_e$  and  $\nu_x$ . This nucleosynthesis process is called the “ $\nu$ -process”, which in contrast to the “ $\nu p$ -process” lacks the free protons available for increasing neutron richness of the material [45]. One noticeable effect of neutrino-nucleus interactions could be suppression of the high energy tail of the  $\nu_e$  spectrum.  $\nu_e$  can interact with nuclei via charged-current inverse beta decay, converting a neutron in the nucleus to a proton and placing the nucleus in an excited state that decays via particle emission. The strength of the interaction scales with the number of neutrons in the nucleus and the energy of the neutrino.

### 3.1 Supernova Neutrino Detection

Even though the impact of neutrino-matter interactions in core-collapse supernovae appears to be limited to the electrons and nucleons present in the heated stellar medium, neutrinos produced in these events carry other valuable information and as a result have dedicated supernova neutrino observatories for their detection. Once neutrinos become free streaming after bounce,  $\nu_\mu$  and  $\nu_\tau$  will no longer have the energy necessary for charged current interactions with matter and are no longer able to thermalize at hotter temperatures corresponding to smaller radii. In neutron rich material,  $\bar{\nu}_e$  interact much less via charged current and therefore decouple sooner than  $\nu_e$ . One goal of observational supernova neutrino physics is to confirm this hierarchy of average neutrino energy. Oscillations occurring as neutrinos travel through the dense matter are predicted to have different consequences depending upon the mass ordering, creating an observable difference in the observed energy spectra of  $\nu_e$  and  $\bar{\nu}_e$ . In observing the light spectrum from nuclei in the ejected material it is possible to search for spectral lines of elements resulting from neutrino induced nucleosynthesis and compare relative abundances to gain insight to the magnitude of these effects within the supernova. A goal of

supernova simulations is to reproduce the isotopic abundances observed in nature for core-collapse supernova. Even though neutrinos rarely interact with matter, the weak interaction has a substantial influence in nature at all scales. Neutrinos and by relation weak interactions serve as a different probe with which to study nuclear structure as well as the driving force in core-collapse supernovae.

# Chapter 4

## Coherent Elastic Neutrino-Nucleus Scattering

Coherent elastic neutrino-nucleus scattering (CE $\nu$ NS, pronounced “sevens”) was first predicted in 1974 by Daniel Freedman [46] after the experimental observation of weak neutral-currents that confirmed the unifying theory electro-weak interactions put forth by Glashow-Weinberg and Salam. In consideration of the well-established nature of electron-nucleus scattering, Freedman postulated the similarity of neutrino-nucleus scattering to this process and its role as probe of the weak isospin structure of a nucleus. “Elastic neutrino-nucleus scattering should exhibit a forward peak characterized by the size of the target” and the form-factor should have the same  $Q^2$  (momentum transfer) dependence. Although the process is quite simple in its prediction (depicted in Figure 16) and has a comparatively large cross-section (Figure 17), the difficulty lies in the detection of the resulting low energy nuclear recoil, leading Freedman to caution his proposal as “an act of hubris.” The condition of coherence derives from the quantum-mechanical behavior of point-like particles propagating with wavelengths inversely proportional to their momenta. The length scale of a nucleus corresponds to an optimal neutrino energy of  $\sim 50$  MeV. The cross section of this interaction can be written as:

$$\frac{d\sigma}{dT_{coh}} = \frac{G_F^2 M}{2\pi} \left[ (G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_v}\right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_v} \right] \quad (4.1)$$

$$G_V = (g_V^p Z + g_V^n N) F_{nuc}^V(Q^2)$$

$$G_A = (g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)) F_{nuc}^A(Q^2),$$

where  $G_F$  is the Fermi coupling constant,  $M$  is nuclear mass,  $T$  is recoil energy,  $E_v$  is incident neutrino energy,  $Q$  is momentum transfer,  $F(Q^2)$  is nuclear form factor,  $g_A^{n,p}$  and  $g_V^{n,p}$  are the vector and axial-vector coupling constants for protons and neutrons, and  $Z_{+,-}$  and  $N_{+,-}$  are the number of spin-up and spin-down nucleons [47]. The form factor is point-like ( $F(Q^2) = 1$ ) for small values of  $Q^2$  but will suppress the interaction rate ( $F(Q^2) < 1$ ) when momentum transfer

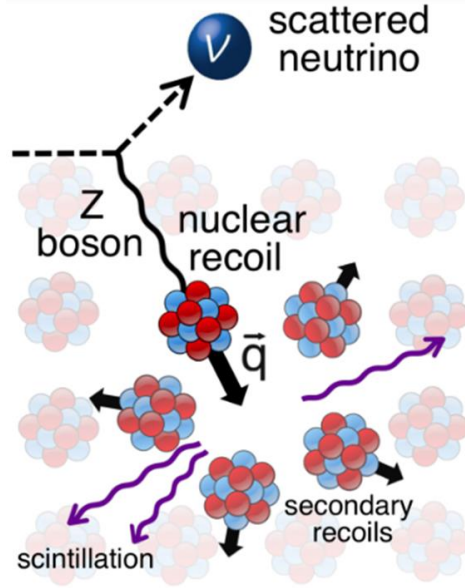


Figure 16. Illustration of CEvNS recoil on nuclear target.

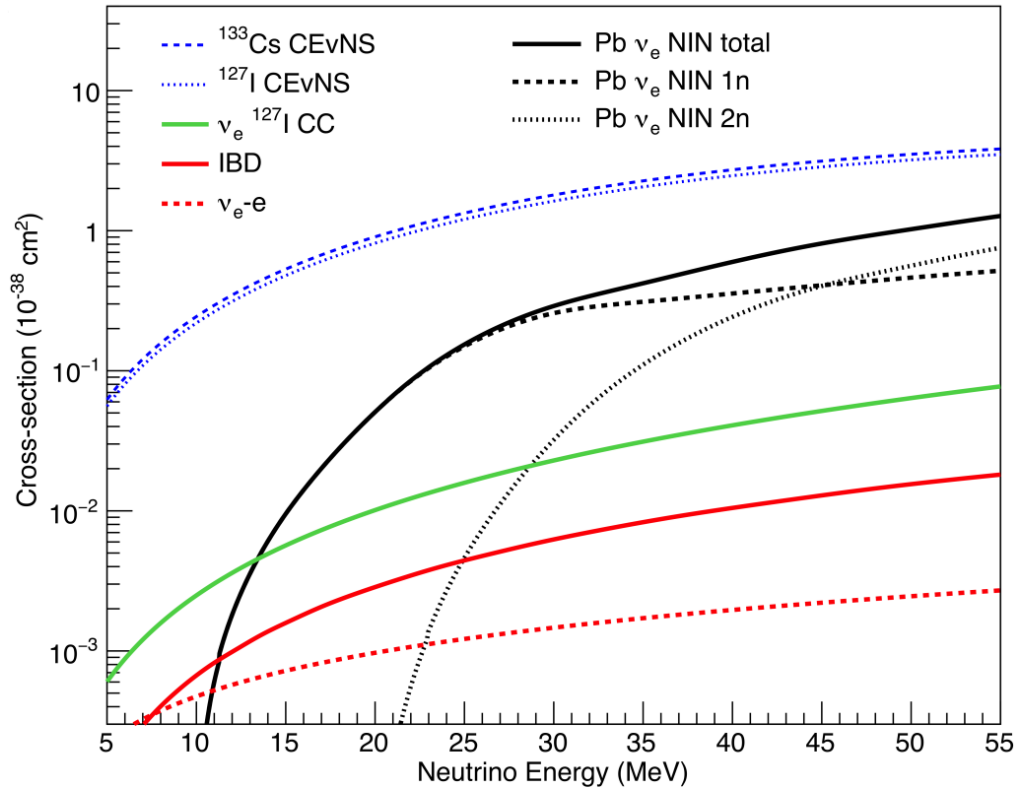


Figure 17. Neutrino cross-section as function of energy. CEvNS cross-section significantly exceeds other possible neutrino interactions due to the enhancement from coherence. Also included and relevant to later sections is the cross-section for neutrino-induced neutrons produced in lead, a possible source of background for CEvNS experiments and of special interest for experiments such as HALO which use this process for the detection of supernova neutrinos.

becomes comparable to the size of the target nucleus. The vector couplings  $G_A$  and  $G_V$  in Eq. 4.1 are defined as:

$$g_V^p = \rho_{vN}^{NC} \left( \frac{1}{2} - 2\hat{\kappa}_{vN} \sin^2 \theta_W \right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}$$

$$g_V^n = -\frac{1}{2}\rho_{vN}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR},$$

where  $\rho_{vN}^{NC}$  and  $\hat{\kappa}_{vN}$  are electroweak parameters,  $\lambda^{uL}$ ,  $\lambda^{dL}$ ,  $\lambda^{dR}$ ,  $\lambda^{uR}$  are radiative corrections from [47] [48], and  $\theta_W$  is the weak mixing angle.

Neutrinos, which only interact through the weak force, are a unique tool to observe the weak charge distribution of the nucleus, where electromagnetic interactions have a much larger range. As Freedman noted, the form-factor dependence of the CE $\nu$ NS cross section and measurement therefore provide a unique probe of nuclear structure. The axial vector contribution to the cross section in 4.1 disappears in the case of even-even nuclei and the cross-section takes the form of:

$$\frac{d\sigma}{dT_{coh}} = \frac{G_f^2 M}{2\pi} G_V^2 \left[ 1 + \left( 1 + \frac{T}{E_v} \right)^2 - \frac{MT}{E_v} \right] \quad (4.2)$$

$$G_V = \left( (g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N \right) F_{nucl}^V(Q^2)$$

where  $\epsilon_{ee}^{uV}$  and  $\epsilon_{ee}^{dV}$  represent non-standard neutrino-quark couplings. CE $\nu$ NS cross-section would be sensitive to non-standard interactions (NSI) of this form and precise measurement of this can rule out models for NSI interactions which can cause effects such as the LMA-D (Dark Large Mixing Angle) solution. Lack of constraint for these non-standard couplings presents an ambiguity in future measurements that could help to determine the mass ordering (Figure 18). Already, the first measurement of CE $\nu$ NS on CsI by the COHERENT Collaboration has placed limits on NSI couplings that disfavor the LMA-D solution of solar neutrino oscillation (Figure 19). More precise measurements are predicted to have sensitivity to completely rule out LMA-D parameter space for NSI couplings, which would resolve the degeneracy between inverted and normal mass ordering determined through oscillation experiments.

In addition to sensitivity to non-standard-interactions and nuclear structure, precise knowledge of CE $\nu$ NS cross-section is an essential element in determination of backgrounds for Dark Matter direct detection experiments, where CE $\nu$ NS interactions are an unavoidable background. Dark Matter direct detection requires sensitive low-background nuclear recoil

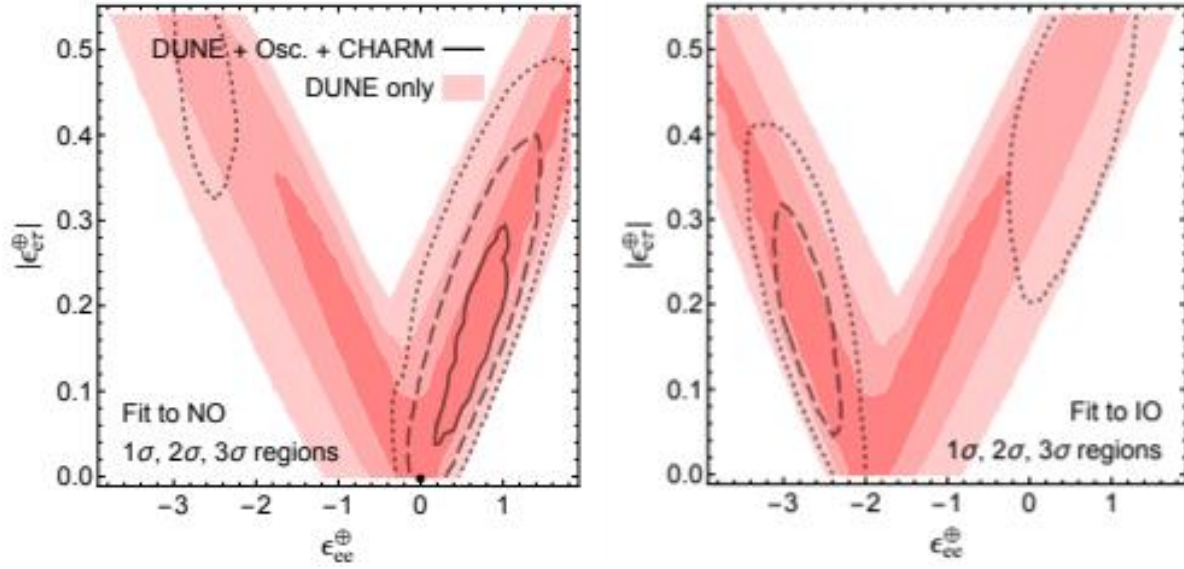


Figure 18. Combined fit to NSI quark coupling parameter space from Oscillation, CHARM and predicted DUNE experimental data. (Left) Fit to Normal Mass Ordering covers parameter space of no NSI where (Right) Fit to Inverted Mass Ordering prefers non-zero NSI parameters.

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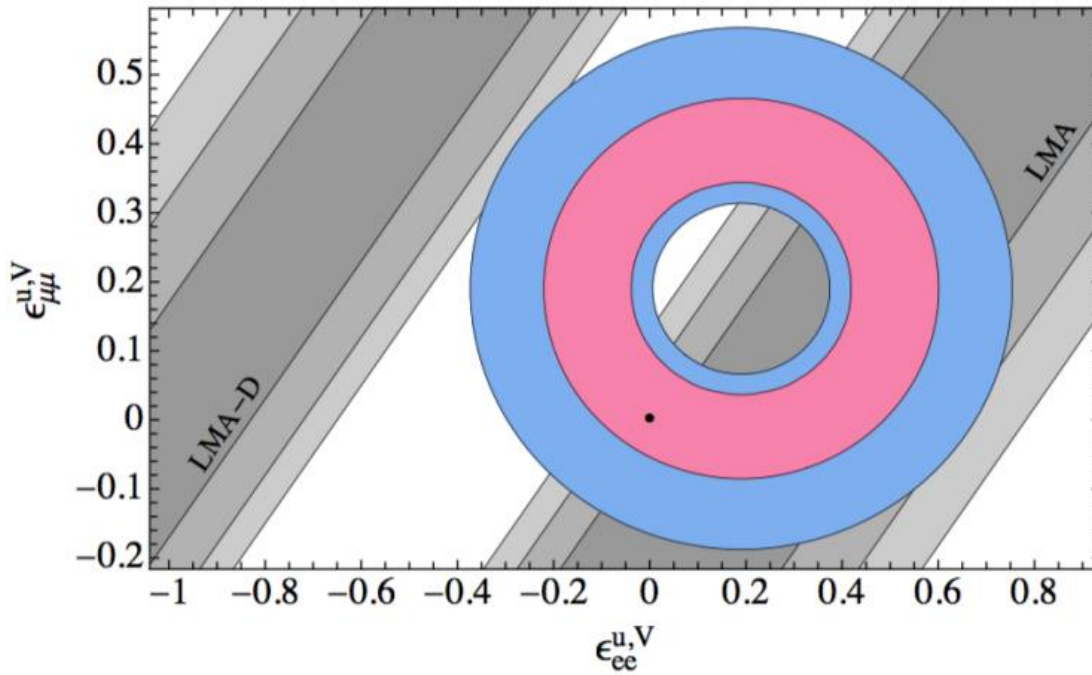


Figure 19. COHERENT imposed limits on NSI parameter space with LMA and LMA-D solution for solar neutrinos.

detectors: however, neutrinos are impossible to shield against [49]. Already these experiments are achieving sensitivity approaching what is known as the “neutrino floor” for these experiments (Figure 20). Neutrinos of different origin (and energy spectrum) produce nuclear recoils via CE $\nu$ NS interactions with the detectors’ target nuclei that mimic the nuclear recoils that would be seen by the recoil of theoretical dark matter candidates of different mass.

## 4.1 The COHERENT Experiment

The COHERENT experiment is an international collaboration bringing together participating institutions for the common goal of the first experimental detection of coherent elastic neutrino-nucleus scattering, leveraging the advancement of low-background, low-energy nuclear recoil detectors and the Spallation Neutron Source located at Oak Ridge National Laboratory of East Tennessee [1]. In addition to first detection, COHERENT aims to test the predicted  $N^2$ -dependence of CE $\nu$ NS cross section with multiple nuclear targets (Figure 21). Already, COHERENT Collaboration has accomplished its goal of first CE $\nu$ NS detection using sodium-doped cesium iodide crystal [50] and now also liquid argon [51], with future plans for high-purity germanium and presently operating sodium iodide. To meet the low-background requirement for CE $\nu$ NS detection, significant shielding is used to reduce backgrounds resulting from beam activity. When using large masses of shielding elements such as lead and iron, there is the possibility of a background arising from inelastic neutrino interactions with these nuclei when the interaction results in neutron emission which can produce low energy nuclear recoils. As such, there is a secondary physics goal of COHERENT for measurement of the inelastic background with its own physics case [5] [52] [53], as these cross-sections are computationally unfeasible to calculate precisely, as well as complimenting CE $\nu$ NS detection with better knowledge of backgrounds [2] [3] [4].

Even with shielding, it is not possible to stop all beam-related backgrounds. The neutrino flux falls off like  $1/r^2$  and so ideally, detectors should be as close to the source as possible while mitigating backgrounds. Most important are fast neutrons, which mimic nuclear recoils and overlap in time with the prompt signal region of neutrino production. As the SNS is primarily a neutron production facility understanding beam related neutron background is of interest for both CE $\nu$ NS and the secondary goal of the measurement of inelastic neutrino-nucleus interactions.

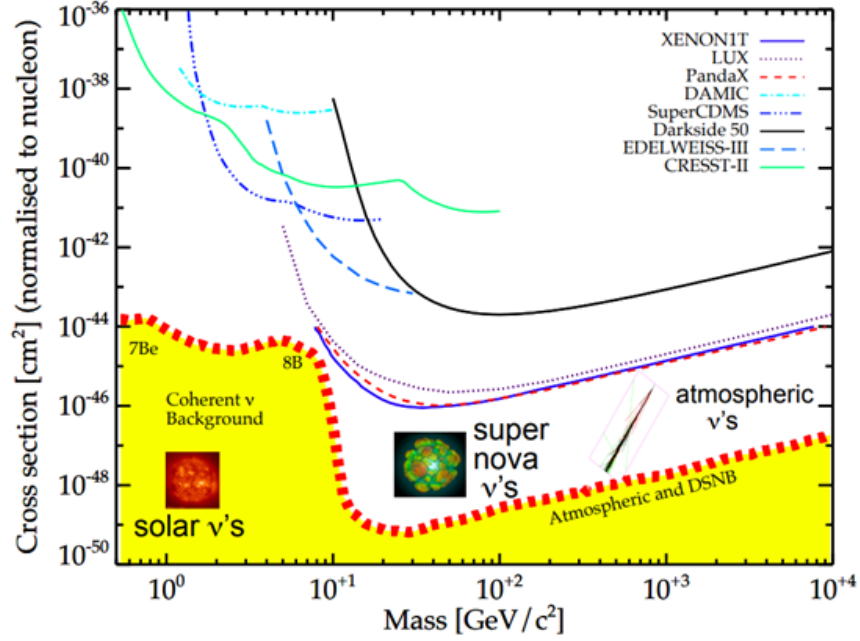


Figure 20. "Neutrino Floor" for Dark Matter direct detection experiment existing from unavoidable  $CE\nu NS$  interactions. Abscissa is mass of dark matter candidate [49].

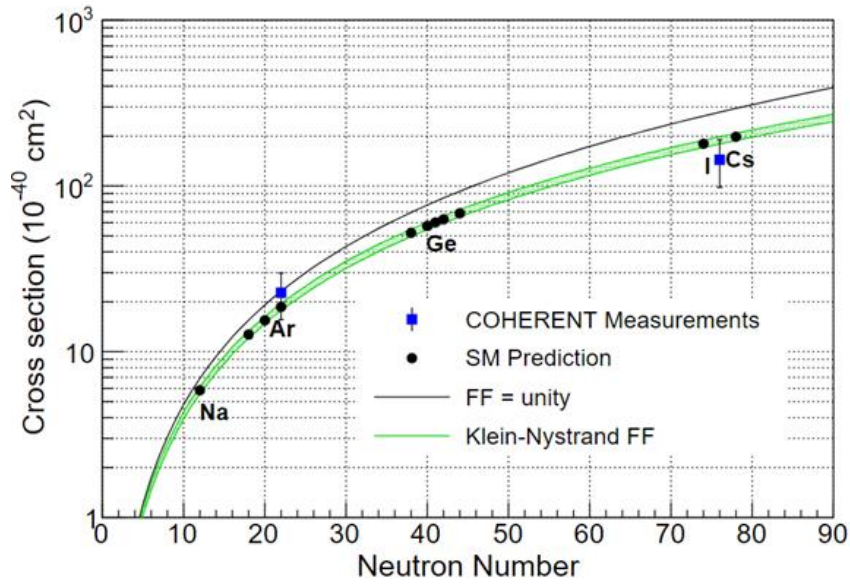


Figure 21.  $CE\nu NS$  cross section dependence on neutron number. In black is the prediction for  $F(Q) = 1$ , representing a point-like nucleus. In green is Klein-Nystrand form-factor predictions implying an increasing spatial distribution of the nucleus as more neutrons, e.g. larger nucleus, are added. The two data points from the COHERENT experiments  $CE\nu NS$  measurement with CsI and liquid argon target agree with a Klein-Nystrand within error.

For this, COHERENT has employed multiple detectors in the pursuit of this. Among these are the Neutron Scatter Camera [54], Multiplicity and Recoil Spectrometer [55], SciBath [56] [57] [58], Eljen Cell at CsI location [50], and most recently the Neutron Timing Cart measurement which studies the variable flux of beam-related neutrons (BRNs) along the hallway. A graphic of some of the past and present detector locations is shown in Figure 22 and total exposure for all COHERENT detectors in Figure 23.

## 4.2 SNS Neutrino Source

The Spallation Neutron Source of Oak Ridge National Laboratory is a neutron production facility powered by a linear accelerator that produces 1 GeV protons that are bunched into  $10^{14}$  protons per bunch in an accumulator ring. The proton bunches are then directed into a liquid mercury target at a rate of 60 Hz with a pulse duration of 380 ns full-width half-max, with a total beam power of up to 1.4 MW during operation [59]. SNS is currently the most powerful pulsed neutrino source in the world. In comparison with other facilities (Figure 24) by power vs. background rejection factor, where the top-right corner is best for neutrino experiments, we can see SNS presently excels in both categories.

The protons break apart the neutron rich mercury target nuclei, producing neutrons, pions and other spallation products. Most spallation and decay products are stopped in the abundant shielding surrounding the target, but neutrinos produced will easily escape the shielding. An average of  $\sim 0.08$  pions per proton are produced, resulting in a neutrino flux of  $4.3 \times 10^7$  neutrinos/cm<sup>2</sup>/s at 20 meters distance from the target for 1 MW beam power. The pulsed nature of the SNS allows for significant ( $\sim 10^5$ ) reduction of steady-state background. Furthermore, the beam energy of 1 GeV produces mostly pions which quickly come to rest in the dense mercury target, providing a clean source of neutrinos from decay-at-rest pions (Figure 25) [60]. Decay-at-rest pions produce three species of neutrinos; the first comes from the decay of the pion:  $\pi^+ \rightarrow \mu^+ + \nu_\mu$  which are mono-energetic 29.8 MeV and in time with the beam. Low energy muons from pion decay travel only a few millimeters quickly come to rest as well. Then two more neutrinos from the decay of the muon:  $\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$  which are delayed by the 2.2  $\mu$ s lifetime of the muon and have a continuous energy spectrum up to  $\sim 50$  MeV.

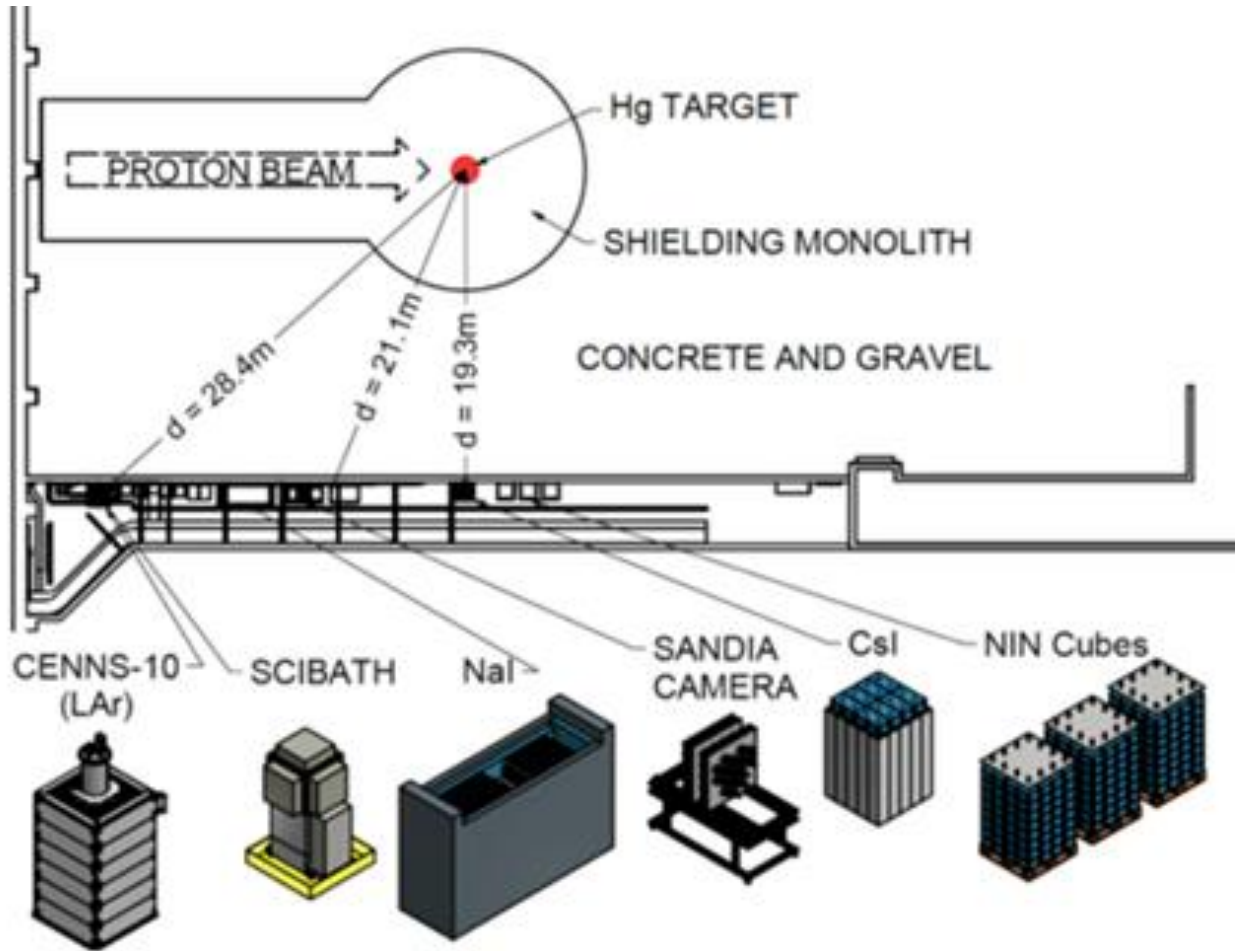


Figure 22. Diagram detailing past and present detector locations along “Neutrino” alley.

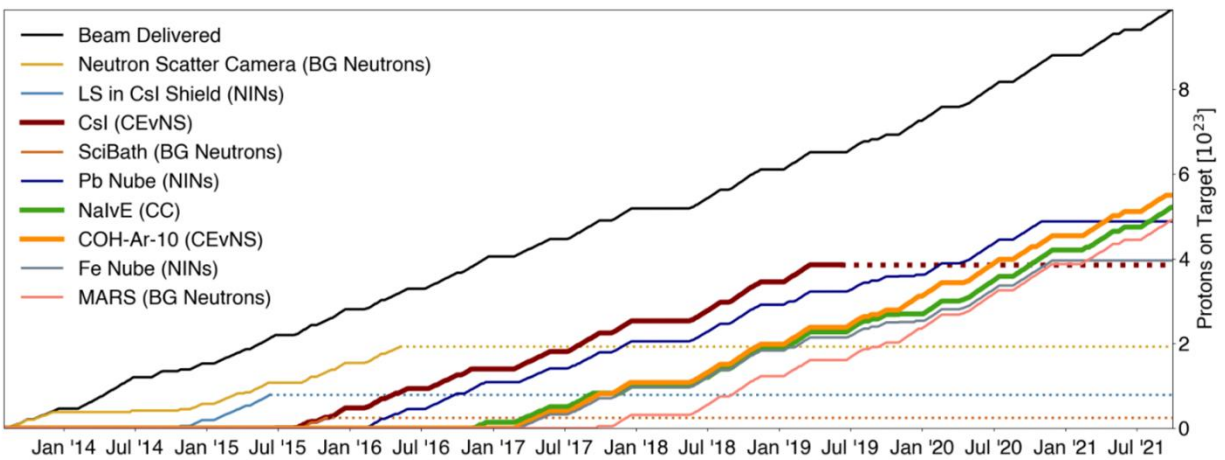


Figure 23. Accumulated exposure of protons-on-target for various detectors deployed by COHERENT.

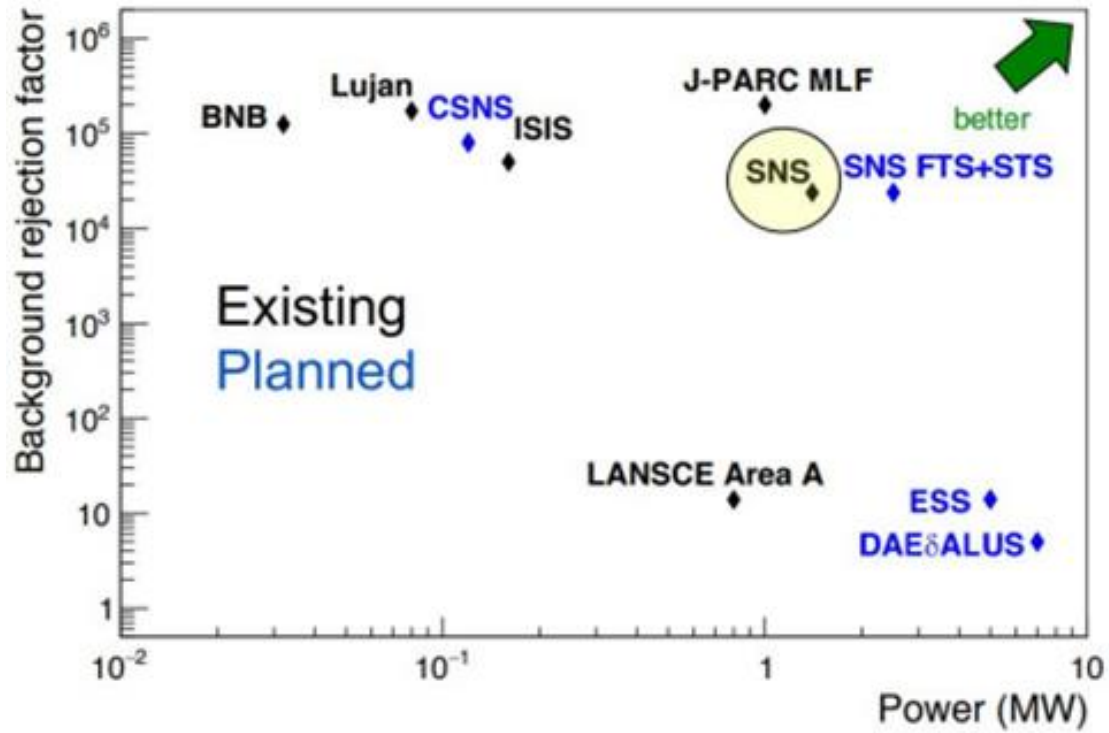


Figure 24. List of planned and existing Pion Decay-At-Rest Neutrino Production facilities. Present SNS is highlighted by the yellow circle and blue is performance after planned upgrades that include a second target station.

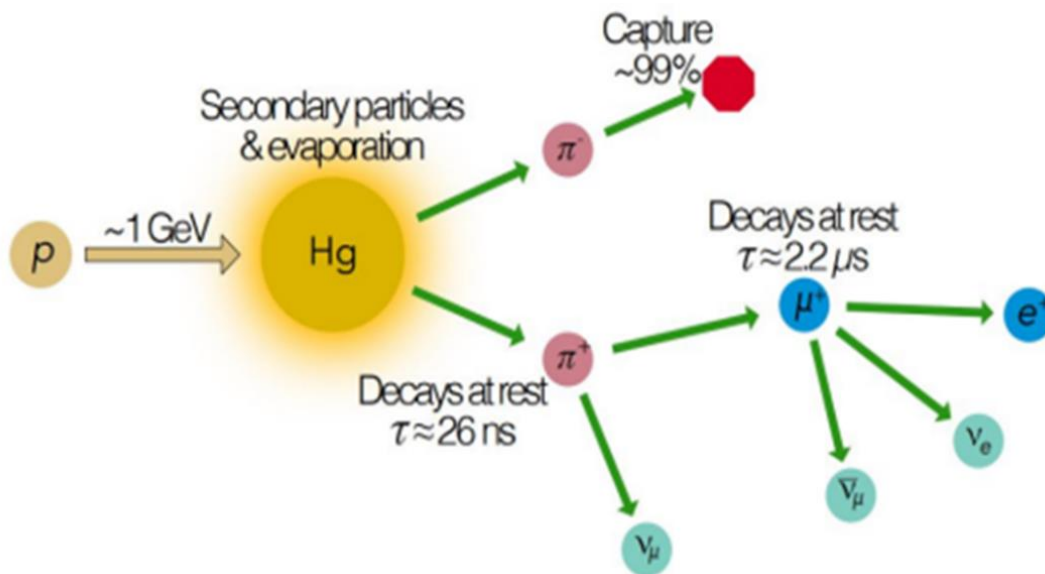


Figure 25. Neutrino production at the SNS.

## 4.3 SNS Neutrino Source Simulations

The error arising from the SNS neutrino flux is the largest systematic uncertainty in the Ar result [51] and the second largest uncertainty in the first CsI result [50]. And with updated measurements of CsI quenching factor this becomes the dominant systematic error in the final CsI result. Precision understanding of the SNS neutrino flux is crucial for the full physics potential of COHERENT cross-section measurements. Simulations of SNS neutrino flux are performed within the GEANT4 [7] Monte Carlo framework with a detailed model of the SNS target to calculate the expected neutrino flux for signal predictions with COHERENT detectors. Simulations using four standard physics lists are compared against available world  $\pi^+$ -production data. However, Hg-target data is not available at low proton energies and data sets near 1 GeV are limited, and most pion-production cross-sections are measured using thin target data which cannot account for energy-loss in the half-meter dense target such as that of the SNS. The choice of physics model is validated by comparison of pion-production measurements of other targets for typically higher energy.

The choice of physics list is determined by comparison of Geant4 simulation to the Norbury-Townsend parameterization developed to match data from proton-nucleus and nucleus-nucleus pion-production (Figure 26) where QGSP\_BERT physics list is favored for hadron production and finds the best agreement [61]. This is then compared to pion-production data from HARP [62] (and HARP-CDP), the Hadron Production Experiment operated at CERN's Proton Synchrotron with incident proton momentum between 1.5 GeV/c to 15 GeV/c on various targets (Figure 27). Although there is some discrepancy in angular and momentum correlation of pion-production between simulation and data, integration over the angular and momentum distribution yields agreement with total cross-section at the 10% level, whereas other physics models overpredict the HARP  $p + {}^{208}\text{Pb}$  data. Because the SNS is a pion decay-at-rest neutrino source, only the total cross-section is significant for source simulation. QGSP\_BERT finds the best agreement with thin target data, however the SNS operates using a half-meter target where proton energy loss and secondary particle interactions influence observed neutrino-flux. Our simulations of the SNS indicate that approximately 25% of pions produced do not result in decay.

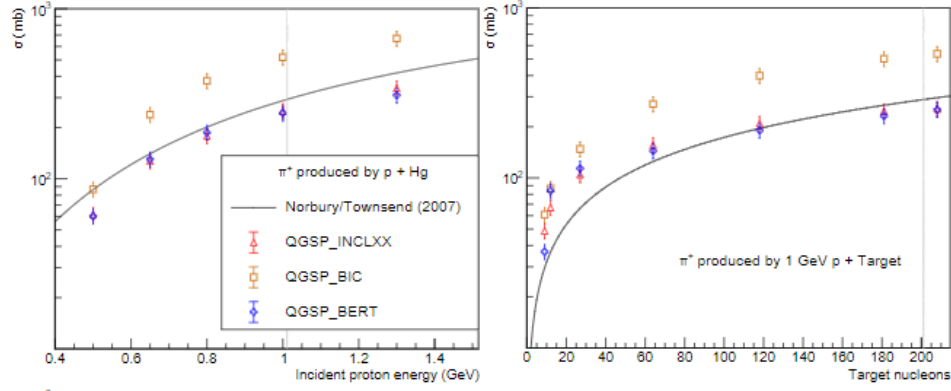


Figure 26. Comparisons of the Norbury-Townsend parameterization and Geant4 model predictions of total pion-production cross-section. (Left) Dependence of total cross section on incident proton energy for a mercury target. The vertical line indicates the current SNS operating energy of 1.011 GeV. (Right) Dependence of total cross-section on target nucleus for a proton energy of 1 GeV. The vertical line represents a mercury target.

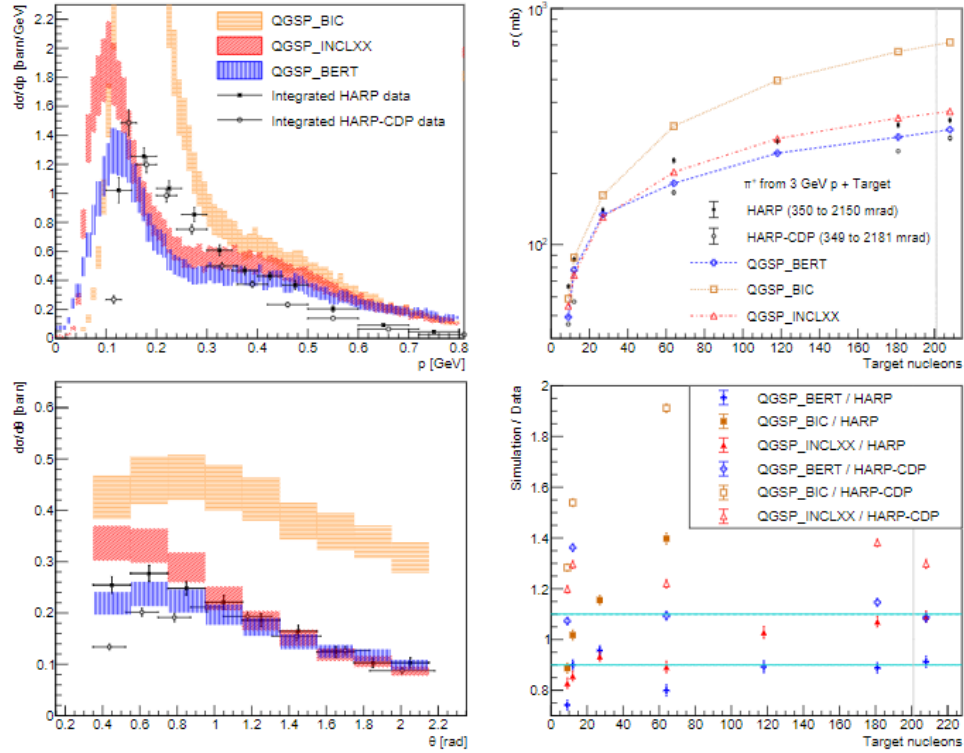


Figure 27. Comparison of measured differential cross-sections of  $\pi^+$  production from 3 GeV/c  $p+^{208}\text{Pb}$  to Geant4 physics lists. (Top Left) HARP and HARP-CDP data were integrated over their respective angular regions and compared to simulation integrated from 350 to 2150 mrad in production angle. (Bottom Left) HARP and HARP-CDP data were integrated from 0.1 to 0.8 GeV/c in momentum and compared to simulation integrated over the same region. (Top Right) The HARP data and Geant4 model predictions of the pion-production cross-section integrated over both angular and momentum intervals of left plots, but with HARP-CDP is integrated over 349-2181 mrad. (Bottom Right) Ratio of Geant4 simulated predictions to the central values of the data, plotted with an uncertainty on all three simulations shown as data error / central value. The horizontal cyan lines mark a  $\pm 10\%$  uncertainty band. The vertical gray line on each right plot represents a mercury target.

Simulations performed within the COHERENT Collaboration of neutrino production at the SNS reliably produce the characteristic pion-decay-at-rest neutrino spectra with some contribution from decay-in-flight (DIF), decay in orbit (DIO),  $\mu^-$  capture, and decay-at-rest kaons (Table 2). However, this contribution is small, with simulation predicting SNS to be a decay-at-rest neutrino source of greater than 99% purity, producing 0.262 neutrinos per proton on target at 1 GeV. Simulation is also used to study the energy dependence of neutrino production to account for the changes in SNS operation over a run period, providing a parameterization relating neutrino flux to beam energy. Existing world data is insufficient for precise validation, resulting in an estimated uncertainty of simulated flux of 10% using QGSP\_BERT which cannot be improved without new measurement. Simulated predictions for SNS neutrino spectra and timing distributions are shown in Figure 28.

## 4.4 Background Campaign

In addition to CE $\nu$ NS detectors, multiple auxiliary detectors have been deployed or are currently deployed for the understanding of backgrounds both steady state and beam related. Before finding the best location for the COHERENT detectors, beam related neutron backgrounds were measured at various locations throughout the experiment hall. Fast beam related neutrons can arrive in CE $\nu$ NS detectors in time with the beam and produce nuclear recoils that mimic a CE $\nu$ NS interaction. Background measurements taken with the Neutron Scatter Camera [54] indicate the basement underneath the experiment hall has very low beam (but non-negligible) related neutron flux and has approximately 8 meters water equivalent overburden protection from cosmic rays (Figure 29). This low background location, now known as “Neutrino Alley,” is home to the COHERENT deployment of detectors, with distances ranging from 20 to 30 meters away from the SNS target. The pulsed nature of the SNS beam provides an additional means of steady-state background rejection by only triggering on events in coincidence with the 60 Hz signal corresponding to beam pulses, providing a background rejection factor of  $\sim 10^4$ . It is also possible to reduce prompt beam related backgrounds by searching for CE $\nu$ NS events “delayed” with respect to the SNS pulse by the 2.2 microsecond decay time of the muon. In addition to initial selection of location, multiple ongoing measurements track the beam related neutrons as it has become evident that this background is highly variable for locations along Neutrino Alley. Most recently, the so-called Neutron Timing

Table 2. Breakdown of the parent particles and the processes which create neutrinos for 1 GeV protons at the SNS with an aluminum proton beam window, separated into decay at rest (DAR), decay in flight (DIF),  $\mu^-$  capture, or decay in orbit (DIO).

|                 | $\nu$ / POT | DAR     | DIF     | $\mu^-$ Cap | $\mu^-$ DIO | $\pi^+ / \mu^+$ | $\pi^- / \mu^-$ | $K^+$   |
|-----------------|-------------|---------|---------|-------------|-------------|-----------------|-----------------|---------|
| $\nu_\mu$       | 0.0875      | 98.940% | 0.779%  | 0.196%      | 0.084%      | 99.7185%        | 0.2812%         | 0.0003% |
| $\bar{\nu}_\mu$ | 0.0875      | 99.718% | 0.0282% |             |             | 99.7187%        | 0.2813%         |         |
| $\nu_e$         | 0.0872      | 99.999% | 0.001%  |             |             | 99.9999%        |                 | 0.0001% |
| $\bar{\nu}_e$   | 0.0001      |         | 0.331%  |             | 99.669%     |                 | 100%            |         |

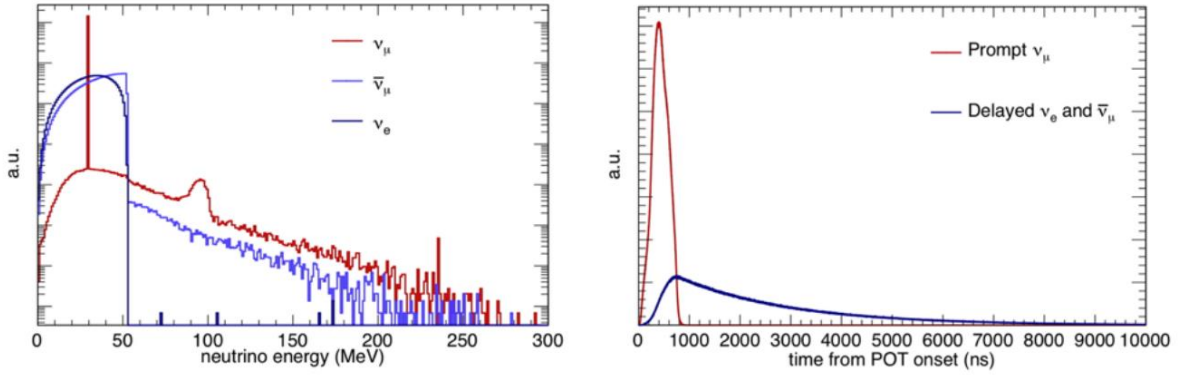


Figure 28. SNS neutrino flux simulation. (Left) Energy spectrum of three neutrino species. Contamination from decay-in-flight pions is reduced by several orders of magnitude and (right) time distribution of these with convolution of proton-on-target pulse width.

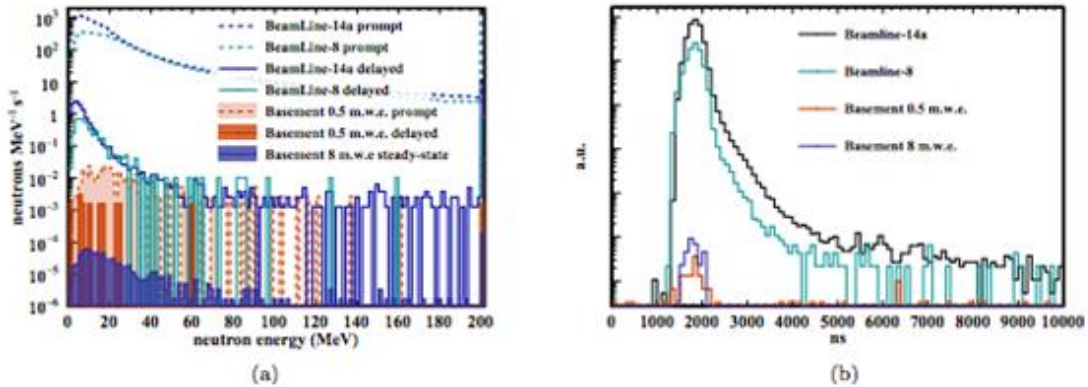


Figure 29. Shown on the left is background neutron energy spectra measured by Neutron Scatter Camera at various locations throughout the experiment hall. On the right is the time distribution of these events with respect to the arrival of the beam. The neutron background in the basement location is orders of magnitude less and is more sharply peaked in time.

Cart has yielded new information on the propagation of neutrons in this area as will be discussed later. The neutron timing cart consists of four five-liter liquid scintillator detectors with pulse-shape discrimination capability. It can easily be repositioned in locations along Neutrino Alley without changing the detector’s configuration. The results of this recent measurement are discussed later in Chapter 6.

## 4.5 First COHERENT Results

The first successful CE $\nu$ NS detection was achieved with a 14.6 kg sodium-doped CsI crystal. Heavy cesium and iodine nuclei have large cross-sections for CE $\nu$ NS that are nearly identical by mass and nuclear composition. High purity CsI crystals produce enough scintillation for detection of nuclear recoils down to a few keV. The quenching factor for this crystal was studied prior to deployment to characterize its response to low energy recoils [63]. Additionally, a measurement was done with an Eljen liquid scintillator detector placed within the planned CsI shielding (though without extra neutron moderator) to measure the small flux of prompt neutrons that reach this location and put a constraint on the possible contribution from neutrino-induced backgrounds that could result from neutrino interactions in the surrounding lead. There is a clear indication of signal correlated with beam activity in both time and energy when compared with anti-coincidence data (data measured before expected neutrino arrival time) with only a small contamination of beam-related neutron backgrounds. The final shielding design included an innermost layer of high-density plastic neutron absorber, interior to the lead, to reduce the possibility of neutrino-induced neutrons and the final data observed negligible contribution from this background. The results are consistent with Standard Model prediction at the one-sigma level ( $134 \pm 22$  events observed,  $173 \pm 48$  predicted) and observed CE $\nu$ NS with 6.7-sigma significance (Figure 30).

Since the initial observation of CE $\nu$ NS with CsI[Na], COHERENT has also published first results of detection of CE $\nu$ NS on liquid argon with a total significance for null hypothesis greater than 3-sigma (Figure 31). The detector is a 22 kg fiducial mass of liquid argon with 2 8” PMTs surrounded by reflective layers of PTFE. The PMTs and PTFE were coated with a small  $0.2 \text{ mg/cm}^2$  layer of wavelength-shifting tetraphenyl-butadiene (TPB) to shift scintillation light to a wavelength where the PMTs is most efficient. Argon scintillation has “fast” ( $\tau \approx 6 \text{ ns}$ ) and

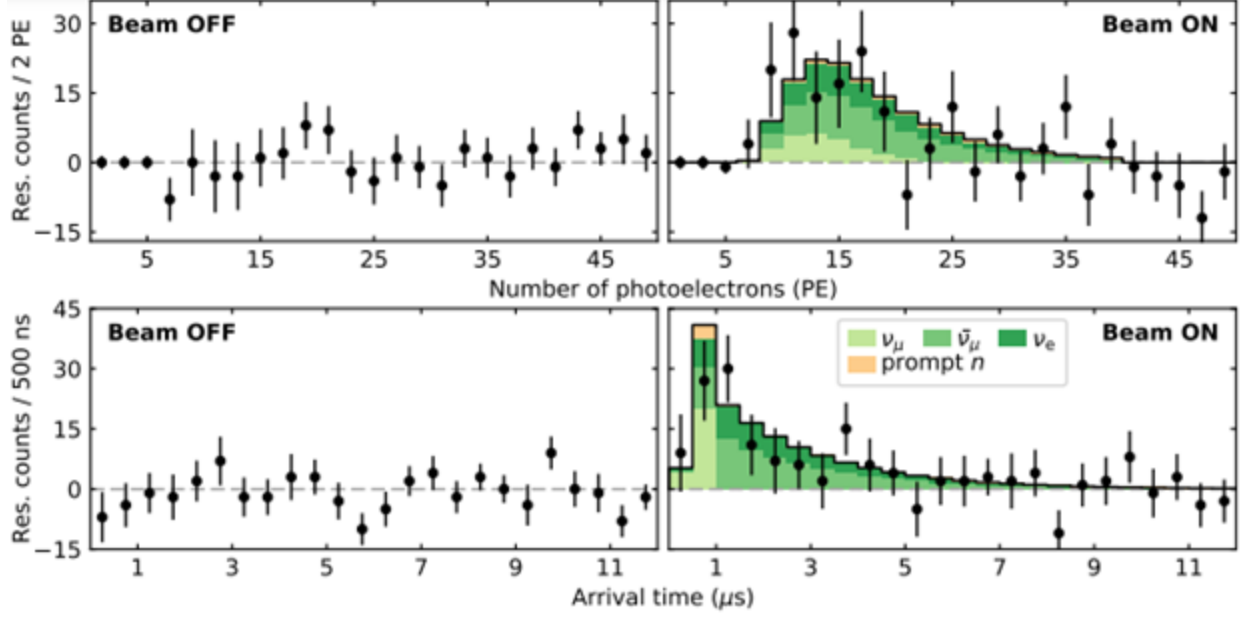


Figure 30. Observation of Coherent Elastic Neutrino-Nucleus Scattering. Shown are residual differences between CsI[Na] signals in the 12  $\mu$ s following POT triggers and those in a 12  $\mu$ s window prior to POT [50]. (Top) Energy, counted in number of photoelectrons and (Bottom) Event arrival time. Steady state backgrounds appear equally in anti-coincident (left) and coincident (right) data and disappear from the subtraction of the two datasets. The data shown is for 153.5 days of “Beam Off” data and 308.1 days of “Beam On” equating to 7.48 GWhr of energy delivered to the target.

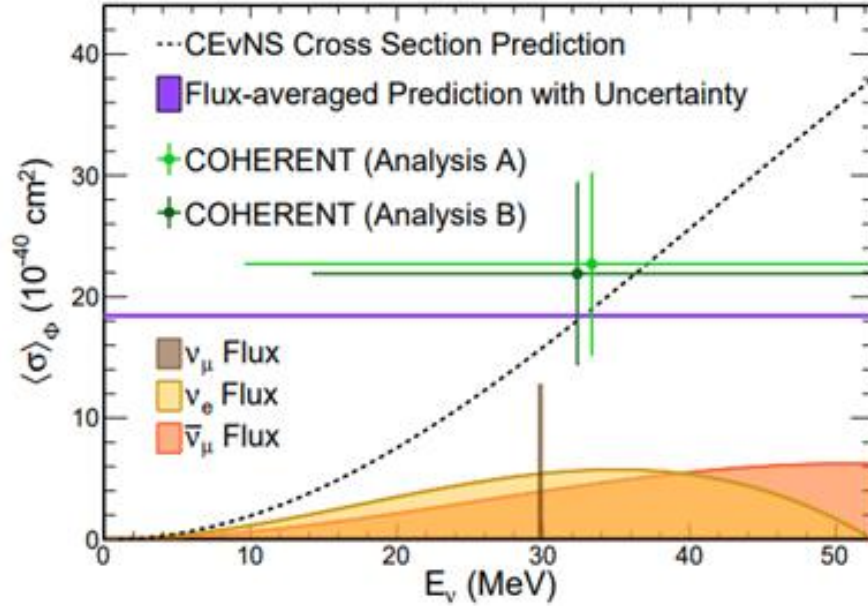


Figure 31. Measured  $\text{CE}\nu\text{NS}$  flux-averaged cross section for two independent analyses, along with SM prediction [51]. Horizontal bars for data points represent energy range of contributing flux, set by NR threshold which differs by analysis. There is 2% uncertainty of theoretical cross-section arising from uncertainty of nuclear form-factor. SNS neutrino flux is shown with arbitrary normalization.

“slow” ( $\tau \approx 1600$  ns) molecular excitations that are differently populated by electron or nuclear recoils, allowing for pulse shape discrimination. An internal calibration source of  $^{83\text{m}}\text{Kr}$  was injected on a weekly basis to track PMT gain and any changes in the detector light output. The first data set includes 6.12 GW\*hr collected from July 2017 to December 2018 and gives a measured CE $\nu$ NS cross section of  $(2.2 \pm 0.7) \cdot 10^{-39} \text{ cm}^2$  in good agreement with the SM predicted cross-section of  $1.8 \cdot 10^{-39} \text{ cm}^2$ . More data has been accumulated since the first measurements of the CsI and Ar detectors. The CsI detector has been decommissioned and the final result has been published at [64]. The Argon detector now has accumulated twice the statistics since the first result and an updated result is expected later in 2022.

# Chapter 5

## Inelastic Neutrino-Nucleus Interactions

Successful measurement of a CE $\nu$ NS interaction requires a careful understanding of all possible backgrounds present. In addition to beam-related neutrons and steady-state backgrounds, there exists another beam-related background arising from inelastic neutrino nucleus interactions. Inelastic neutrino-nucleus interactions are a two-step process in which the incident neutrino interacts with a nucleus, raising it to an excited state. These reactions can either be charged-current, in which a neutron is converted to a proton and the charged lepton carries away the difference in neutrino energy and the nuclear excitation energy, or neutral-current in which the neutrino carries away the energy difference.

Charged-current:  $\nu_e + {}^{208}\text{Pb} \rightarrow e^- + {}^{208}\text{Bi}^*$

Neutral-current:  $\nu_x + {}^{208}\text{Pb} \rightarrow \nu'_x + {}^{208}\text{Pb}^*$

After the initial nuclear excitation, the excited state decays via particle emission: proton, neutron, electron, alpha, or photons. Although core-collapse supernova simulations suggest that neutrino-nucleus interactions have minimal influence on nucleosynthesis taking place in the supernova environment, inelastic charged current neutrino nucleus interactions provide a process by which heavy, neutron rich isotopes can transition to higher proton numbers [52] [53]. Exact cross-section calculations for large nuclei such as lead are computationally unfeasible. The nuclear excitations are first done by random phase approximation (RPA) and the subsequent decays are calculated with statistical models. In literature, this process tends to be of most interest in the context of supernova neutrino physics and calculations for neutron production are done with supernova neutrino spectra as input [3].

Neutrino-induced neutron production from inelastic neutrino-nucleus interactions is of particular interest as a background for CE $\nu$ NS detection because the neutrons produced in nearby shielding components can reach CE $\nu$ NS detectors and produce nuclear recoils of similar energy to a CE $\nu$ NS event and sharing the same time structure of the neutrinos. The charged-current cross-section is roughly half an order of magnitude stronger than neutral-current for neutrino

energies relevant for supernovae or stopped-pion decay. The strength of this interaction scales with the size of the nucleus and for large nuclei such as Pb, becomes comparable to the cross-section for CE $\nu$ NS (see Figure 16). Typical shielding configurations contain large masses of Pb, Fe, and Cu (usually more massive than the detector itself) which can create a non-negligible background of neutrons resulting from inelastic neutrino-nucleus interactions. Other particles emitted will quickly be absorbed in the shielding in which they are produced, whereas neutrons can travel significantly further and interact in detectors. The threshold for neutrino-induced neutron production is the neutron separation energy of the excited nucleus. Calculations for excited states in  $^{208}\text{Pb}$  from charged-current neutrinos ( $\pi\text{DAR}$  energy spectrum) are shown in Figure 32 [2]. For large, neutron-rich nuclei such as Pb, whose single neutron separation energy is about 7 MeV, the threshold is significantly less than the average  $\pi\text{DAR}$  neutrino energy. Two-neutron production is possible as well; there are excitable resonances above the two-neutron separation threshold at roughly 16 MeV for Pb. As the neutrino energy increases, the probability to excite a resonance above the two-neutron separation threshold exceeds single neutron production. When the nucleus decays back to the ground state, the neutron carries away the difference in energy between the separation energy and the nuclear level (Figure 33). In the case of two neutron production, this energy is shared between the two emitted neutrons. As a result, single neutrons will have different energy spectrum than double neutron events.

Neutrino-induced neutron production has not yet been measured before this experiment. Experimental data for inelastic neutrino-nucleus reactions is lacking. Present predictions for neutrino-induced neutron production in lead give as much as 30% difference in cross-section, introducing a large uncertainty into a possible CE $\nu$ NS background. The measurement of this process (NINs) on lead and other target nuclei should provide experimental data for comparison with the predictions of nuclear models. The nucleosynthesis of heavy elements is of interest for supernova simulations seeking to reproduce natural abundances. The neutrino-induced processes occurring at low temperature are the basis of present understanding of how these processes will occur at  $T > 3 \text{ MeV}$  in a hot supernova environment. And as was mentioned in Section 3, this process provides a complimentary method of detection for supernova neutrinos as in the HALO experiment [5].

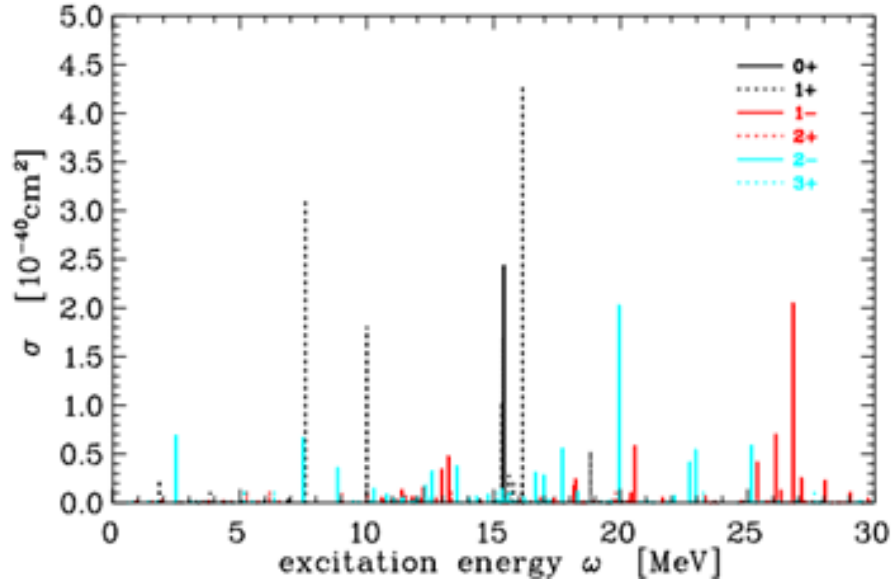


Figure 32. Multipole decomposition of charged-current excitation of  $^{208}\text{Pb}$  from decay-at-rest neutrino energy spectra from [2].

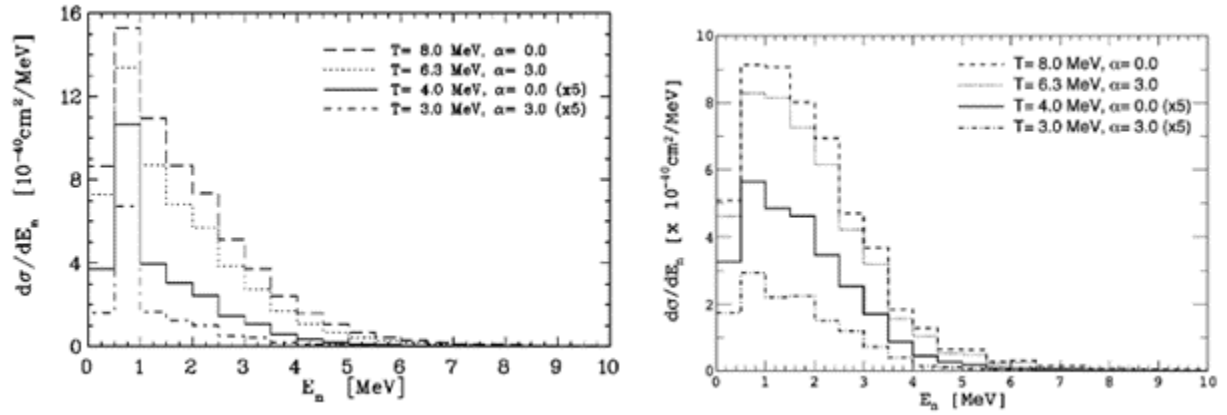


Figure 33. (Left) Charged-current neutrino-induced neutron spectrum in  $^{208}\text{Pb}$  from [2] for supernova neutrino energy distribution. (Right) Neutral-current neutrino-induced neutron spectrum in  $^{208}\text{Pb}$  from supernova neutrino energy distribution. Both spectra include the contributions from  $1n$  and  $2n$  emission.

## 5.1 Neutrino-Induced Neutron Production Models

There are existing predictions for the neutrino-induced neutron cross section on  $^{208}\text{Pb}$  for supernova neutrino energy spectra, and some similar published calculations for decay-at-rest neutrinos. However, there are no published calculations of multi-neutron NIN events or associated decays by other particle emission. The Model of Argon Reaction Low Energy Yields (MARLEY) event generator was recently released, allowing for simulation of low energy, charged-current and neutral-current neutrino-nuclear interactions of allowed transitions [65]. MARLEY was originally designed for neutrino interactions on  $^{40}\text{Ar}$  nuclei but is adaptable for other nuclei, provided measurements of the Gamow-Teller (GT) strength distributions [66] [67]. Although it only supports allowed transitions, it is robust and provides detailed decay information for predicting the observed signal making it a suitable choice as an event generator for the simulation of NINs in the PbNube detector. Comparison of the charged-current and neutral-current cross-section predictions from literature are shown in Tables 3 and 4. Unfortunately, neutral-current cross-sections received a large contribution from forbidden transitions not included in MARLEY at this time. The values of  $B(M1)$  strengths used for neutral-current transitions are taken from studies of  $^{208}\text{Pb}$  from references [68] and [69].

## 5.2 Neutrino-Induced Neutron Supernova Detection

Neutrino-induced neutrons have a large cross-section in comparison to other neutrino cross-sections, and its cross section scales with the size of the nuclear target. While it remains a concerning background for precision CEvNS measurements, it is a viable process by which to detect supernova neutrinos. The HALO (Helium and Lead Observatory) detector is designed for this purpose [5]. Located underground at the Sudbury Neutron Observatory Laboratory, the HALO detector is comprised of 79 tons of lead blocks instrumented with proportional  $^3\text{He}$  neutron detectors selected for high neutron-capture cross-section with a total length of 348 meters. As neutrons are produced by neutrinos from a core-collapse supernova in the lead target, they are moderated by the polypropylene surrounding the  $^3\text{He}$  counters. HALO is mostly sensitive to the charged-current contribution of electron neutrinos and for this serves as a complimentary method of detector for unfolding the flavor composition of a galactic core-collapse supernova event. However, the uncertainty in predictions for cross-section becomes an

Table 3. Calculations of charged-current cross-sections for decay-at-rest electron neutrinos on  $^{208}\text{Pb}$  [70] from MARLEY and existing calculations from Kolbe [2], Volpe [71], Suzuki [4], McLaughlin [72], Athar [73], Lazauskas, [74] and Paar [75].

| Reaction Channel                               | Cross section ( $\times 10^{-40}\text{cm}^2$ ) | Notes                                                     | Reference                |
|------------------------------------------------|------------------------------------------------|-----------------------------------------------------------|--------------------------|
| $^{208}\text{Pb}(\nu_e, e^-)X$                 | 36.23                                          | $g_A/g_{A_{eff}} = 0.7$                                   | Kolbe, et al. (2001)     |
|                                                | 44.39                                          | $g_A/g_{A_{eff}} = 1.0$                                   | Volpe, et al. (2002)     |
|                                                | 43.0                                           | $g_A/g_{A_{eff}} = 1.0$                                   | Suzuki, et al. (2003)    |
|                                                | 29.5                                           | $g_A/g_{A_{eff}} = 0.8$                                   | Suzuki, et al. (2003)    |
|                                                | 32                                             | $g_A/g_{A_{eff}} = 0.8$ ,<br>GT strength from [67]        | Suzuki, et al. (2003)    |
|                                                | 41                                             | $g_A/g_{A_{eff}} = 0.79$                                  | McLaughlin (2004)        |
|                                                | 26.43                                          | $g_A/g_{A_{eff}} = 0.7$                                   | Athar, et al. (2006)     |
|                                                | 49.6                                           |                                                           | Lazauskas, et al. (2007) |
|                                                | 26.43-36.20                                    | $g_A/g_{A_{eff}} = 0.8$<br>various techniques             | Paar, et al. (2008)      |
|                                                | 42.1                                           | $g_A/g_{A_{eff}} = 1$ , allowed,<br>GT strength from [66] | MARLEY                   |
| $^{208}\text{Pb}(\nu_e, e^-n)^{207}\text{Bi}$  | 32.9                                           | $g_A/g_{A_{eff}} = 0.7$                                   | Kolbe, et al. (2001)     |
|                                                | 23.5                                           | $g_A/g_{A_{eff}} = 0.79$                                  | McLaughlin (2004)        |
|                                                | 31.6                                           | $g_A/g_{A_{eff}} = 1$ , allowed,<br>GT strength from [66] | MARLEY                   |
| $^{208}\text{Pb}(\nu_e, e^-2n)^{206}\text{Bi}$ | 13.5                                           | $g_A/g_{A_{eff}} = 0.79$                                  | McLaughlin (2004)        |
|                                                | 7.73                                           | $g_A/g_{A_{eff}} = 1$ , allowed,<br>GT strength from [66] | MARLEY                   |
| $^{208}\text{Pb}(\nu_e, e^-3n)^{205}\text{Bi}$ | 0.4                                            | $g_A/g_{A_{eff}} = 1$ , allowed,<br>GT strength from [66] | MARLEY                   |

Table 4. Neutral-current cross-section calculations for decay-at-rest neutrinos on  $^{208}\text{Pb}$  [70] from MARLEY, Suzuki [4], and Semenov [76]. Lacking forbidden transitions, MARLEY calculates a cross-section a factor of  $\sim 6$  less than literature.

| Reaction Channel                                  | Cross section ( $\times 10^{-40}\text{cm}^2$ ) | Notes                                                                           | Reference             |
|---------------------------------------------------|------------------------------------------------|---------------------------------------------------------------------------------|-----------------------|
| $^{208}\text{Pb}(\nu_x, \nu'_x)X$                 | 4.09                                           | $g_A/g_{A_{eff}} = 1.0$ ,<br>SD and $1^+$ strength, $\nu_e$                     | Suzuki, et al. (2003) |
|                                                   | 2.087                                          | $\nu_e + \bar{\nu}_\mu$                                                         | S. V. Semenov (2017)  |
|                                                   | 0.68                                           | $\nu_e$ , $g_A/g_{A_{eff}} = 1$ , allowed,<br>M1 strength from [68, 69]         | MARLEY                |
|                                                   | 0.48                                           | $\nu_\mu$ , $g_A/g_{A_{eff}} = 1$ , allowed,<br>M1 strength from [68, 69]       | MARLEY                |
|                                                   | 0.97                                           | $\bar{\nu}_\mu$ , $g_A/g_{A_{eff}} = 1$ , allowed,<br>M1 strength from [68, 69] | MARLEY                |
|                                                   | 0.46                                           | $\nu_e$ , $g_A/g_{A_{eff}} = 1$ , allowed,<br>M1 strength from [68, 69]         | MARLEY                |
| $^{208}\text{Pb}(\nu_x, \nu'_x n)^{207}\text{Pb}$ | 0.33                                           | $\nu_\mu$ , $g_A/g_{A_{eff}} = 1$ , allowed,<br>M1 strength from [68, 69]       | MARLEY                |
|                                                   | 0.65                                           | $\bar{\nu}_\mu$ , $g_A/g_{A_{eff}} = 1$ , allowed,<br>M1 strength from [68, 69] | MARLEY                |
|                                                   |                                                |                                                                                 |                       |

uncertainty for expected signal for any event detected in HALO (Picture of HALO without counters in place, Figure 34).

HALO is a part of the global Supernova Early Warning System (SNEWS) and has been taking data over the last 10 years but has yet to see any signal. SNEWS is a network of neutrino detectors around the globe designed to give early warning to astronomers in the event of a supernova in our galaxy or nearby galaxies such as the Large Magellanic Cloud or the Canis Major dwarf galaxy. SNEWS estimates a directional precision of approximately 5 degrees and as of the time of writing this thesis, SNEWS has not issued any supernova alerts [77]. Recently, HALO collaboration has started to consider an even more ambitious proposal for the SuperHALO detector with ten times the fiducial mass with possible location at the LNGS (Laboratory Nazionale at Gran Sasso). Precise characterization of NINs is required for this proposal to be fully considered.



Figure 34. HALO detector in place at SNOLAB facility. The empty cavities are where the  $^3\text{He}$  proportional counters are to be placed.

# Chapter 6

## Neutrino-Induced Neutron Measurements at the SNS

As part of the dedicated background campaign, and with its own physics case, the COHERENT collaboration has deployed dedicated detectors with iron and lead target for the measurement of neutrino-induced neutrons, dubbed the “Neutrino Cubes”. Experimental results for one of these detectors, lead, is the focus of this dissertation. As mentioned before, inelastic neutrino-nucleus interactions that produce neutrons is an unavoidable background for CE $\nu$ NS detectors that employ large masses of shielding material comprised of heavy nuclei surrounding the neutrino detector. The mass of shielding is usually many times larger than the masses of neutrino detectors therefore neutrino interactions in the shielding material becomes significant. As a result, even if the non-CE $\nu$ NS cross section is smaller, NINs can produce a significant background. Therefore, knowledge of the cross-section for neutrino-induced neutrons becomes important. This process has not yet been experimentally measured for lead, and theoretical calculations of cross-section are computationally difficult to predict for large nuclei leading to large uncertainty in cross-section predictions of this process. Furthermore, the background rejection provided by the pulsed nature of the SNS is not effective for NINs because these neutrons produce similar nuclear recoils and share the same time profile as CE $\nu$ NS.

### 6.1 The Neutrino Cube Detector

Neutrino-induced neutron detectors or “neutrino cubes” (or “nubes”) as they are named for their rectangular shape, are assembled on top of a 1” aluminum plate secured to a steel palette. For the lead nube, a steel pedestal supports 980 kg of lead, cast with tapered narrow hollow regions for aluminum support rods and 4 larger tapered cylindrical cavities for the placement of four Eljen-301 organic liquid scintillator cells. Organic liquid scintillators provide pulse shape discrimination capability between gamma and neutron signals. Each cell is 4.5” in diameter and 9” height and equipped with an Electron Tubes 9821-KEB 3”-PMT. The cast lead is surrounded on its sides by four 20 mm x 16” x 36” EJ-200 plastic scintillator muon veto panels and a 2” x 17.5” x 17.5” plastic scintillator panel on top. The muon veto panels are wrapped in 2

mm reflective mylar and 0.015" HDPE film. Each panel has two 2" PMTS mounted with 3D printed acrylic light guides. 9" x 18" x 6" water bricks are placed outside of the muon veto panels and below the steel pedestal supporting the lead, providing roughly 9" of water shielding on all sides for background neutron moderator. Support rods extend through the assembly to support an aluminum roof plate. A smaller aluminum plate suspended from the roof plate supports water bricks directly above the lead volume. After the deployment of the second nube, the iron neutrino cube, the four original liquid scintillator detectors were split between the two neutrino cubes. After that, the available lead detector cavities were filled with other slightly smaller (1.4 L) hexagonal organic liquid scintillator cells. The liquid scintillator cells and engineering drawing of the lead NUBE design are shown in Figures 35 and 36. An image of the deployment of the lead neutrino cube and the electronics rack is shown in Figure 37.

## 6.2 Data Acquisition

Data collection system is based on commercial electronics in VME standard. The following electronic modules were used for the recording of Neutrino Cubes detector data:

- CAEN V1730 Digitizer
- CAEN V895 Discriminator – Each of the muon veto panel PMTs has a dedicated channel. A signal whose amplitude is proportional to the number of muon veto channels active is sent to the digitizer. Individual muon veto signal amplitudes are not recorded.
- CAEN V1495 FPGA/trigger unit – VME Card with user programmable FPGA. Carries out muon veto checks.
- CAEN V2718 – Optical VME bridge card.
- CAEN A3818 – PCIe card
- CAEN 4527 HV Mainframe

Trigger logic for the NIN detectors is similar CEvNS detection by only searching for events in time with the beam spill incident on the SNS target. This allowed for significant reduction of steady-state backgrounds. Additionally, this greatly reduces the amount of space required for data storage and processing. The data acquisition triggers on a coincidence of protons-on-target (POT) signal and activity above threshold any of the four detector channels in the Nube within the next 20 microseconds. The POT signal is a logical signal produced by the SNS, called Event 39. Uncertainty in the arrival time of the beam with respect to Event 39 is

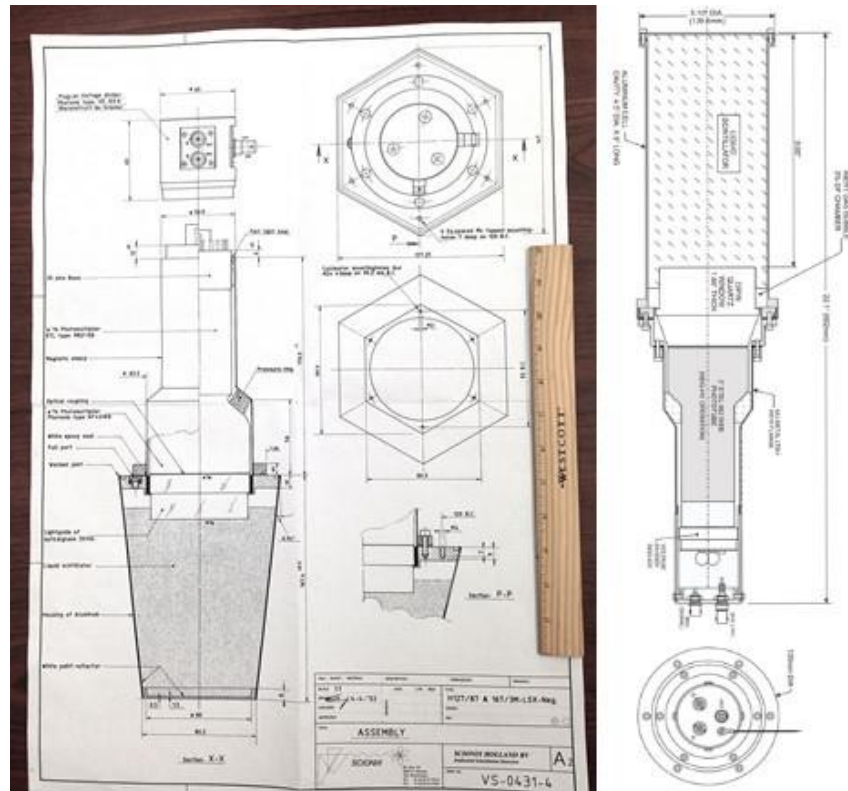


Figure 35. (Left) Hexagonal 1.4L liquid scintillator and (Right) custom Eljen (EJ-301) cylindrical liquid scintillator detectors.

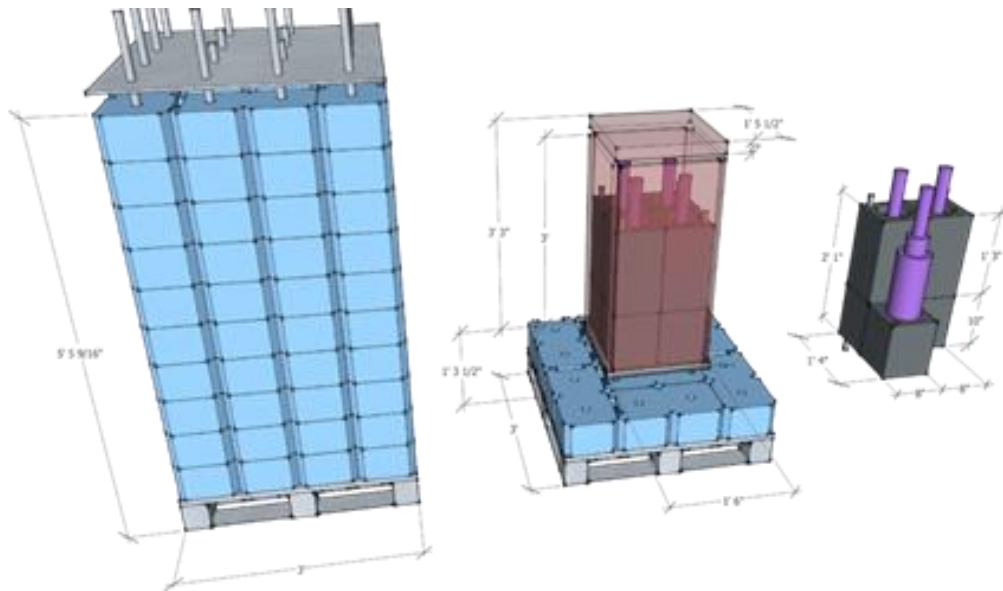


Figure 36. Neutrino Cube detector assembly surrounded by water bricks [70]. (Middle) Interior muon panels (transparent) with lead volume and detectors atop steel pedestal. (Right) Lead volume with detector cells.



*Figure 37. NUBES electronics rack with NaI detector positioned between this and the two active Neutrino Cubes on the left.*

negligible for our measurements. Either the scintillator cells or the Event 39 can start a coincidence window. A 16-channel, 500-MHz, 14-bit CAEN 1730 digitizer records waveforms for 80 microseconds. Events where Event 39 starts the coincidence window fall at about 28 microseconds in the waveform. The recorded data consists of the four detector channel waveforms, the summed muon veto output, and Events 39 and 61 (Event 61 is another SNS timing signal, explained in next section). In addition to production mode, where the DAQ triggers on coincidences of channel triggers and the liquid scintillator channels, the DAQ can be operated to trigger on just the liquid scintillators or muon veto test mode for detector health checks. During normal operation, these checks occur randomly three times a day. The waveforms are stored as TWaveform objects in ROOT TTrees to be processed later [78]. Figure 38 shows a typical event that would be recorded in the DAQ.

## 6.3 Data Processing

Event processing is done trigger-by-trigger, beginning with timing signals from the SNS indicating beam activity. The timing signals, Events 39 and 61 are logical pulses for which a level threshold of 6000 ADC is used to identify onset time of pulses in these channels. Event 39 occurs 60 times per second in time with protons on target during normal SNS operation. However, every 600<sup>th</sup> Event 39 lacks the corresponding beam spill, indicated by the absence of an Event 61 signal. Next, the muon veto pulses are processed. This is done by first calculating the nominal baseline value from the beginning 1000 samples of the veto channel waveform then determining the mean and FWHM of this distribution. These are used as inputs for a conditional moving-average (CMA) filter which removes long timescale oscillations on the baseline while not affecting the integral of a pulse [63]. The effect of this is demonstrated in Figure 39. This is done by calculating the running baseline average for a 250-sample window, while excluding samples that are greater than three standard deviations from baseline. Pulses in the muon veto channel are logic pulses, with pulse amplitude corresponding to the number of active veto PMTs above discriminator threshold. The logic signal is 200 ns wide, and so a hold-off time of 230 ns is used prior to search for additional veto pulses in the waveform. The baseline, peak height, and onset time are recorded for veto signals.

Use of liquid scintillators grants the ability for pulse shape discrimination (PSD) where electronic recoils and nuclear recoils have distinguishable differences in the shape of their

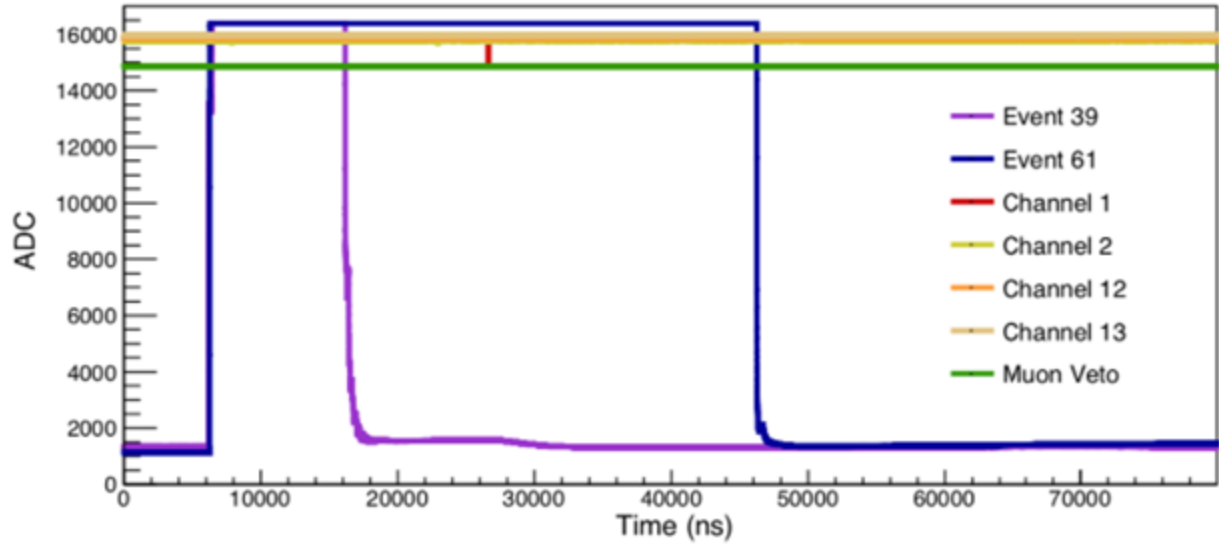


Figure 38. Typical triggered DAQ event [70]. Events 39 and 61 are timing signals from the SNS indicating beam activity. The muon veto waveform is a logical sum proportional to the number of veto PMTs over threshold from the five surrounding panels.

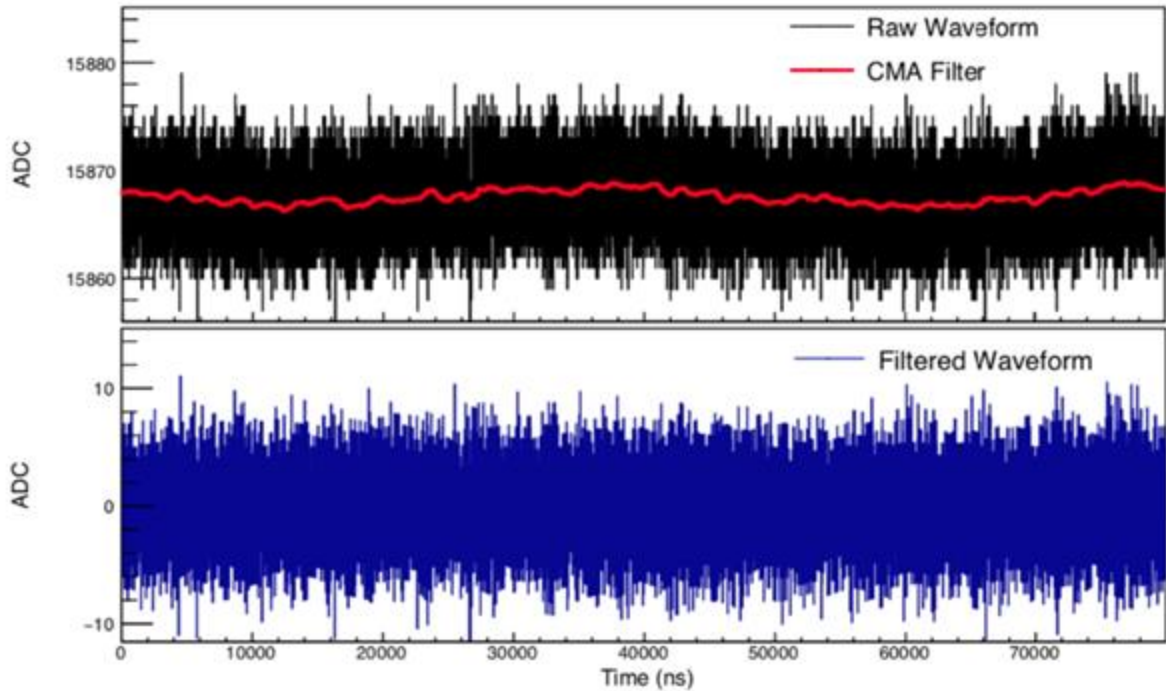


Figure 39. (Top) Example of muon veto trace and the baseline determined by the CMA filter [70]. (Bottom) is the resulting waveform with CMA-determined baseline subtracted.

scintillation pulse (Figure 40). Neutrons produce longer-lived molecular excitations that decay by scintillation relative to electron/gamma recoils. It is therefore possible to separate neutron and gamma interactions by comparing the ratio of total integral to the tail integral of the longer-lived scintillation component. The onset time of a liquid scintillator pulse was determined by a constant fraction discriminator (CFD) set to 20% of the pulse peak amplitude. Ten nanoseconds prior to onset of each liquid scintillator pulse are integrated and 390 nanoseconds afterwards for integration. A second integral of the latter 355-360 nanoseconds (start of tail integral is optimized for each detector) constitutes the “tail integral.” The pulse shape discrimination factor (PSD) is defined as the ratio of tail integral to full integral. Other forms of PSD were considered, and only the boosted decision tree (BDT) showed significant improvement over standard PSD for  $^{252}\text{Cf}$  calibration data. However, BDT PSD was not included in final analysis over concerns of change in PSD behavior over time, such that BDT parameters trained on  $^{252}\text{Cf}$  data would not be able to account for time-dependent changes.

Liquid scintillator detector channels are processed similar to muon veto channels, with a few key differences. The CMA filter is similarly applied to liquid scintillator channels. After filtering, liquid scintillator pulses are identified with a threshold of 200 ADC intended to reproduce the nominal hardware trigger threshold. A hold-off time of 30 microseconds was used to avoid triggering on the electronic ringing that was present in the waveforms. Without this, there were additional pulses occurring for several microseconds after a triggered event that had abnormal PSD parameters (Figure 41). The effect of this hold-off time on detector live-time was less than one percent for all channels. A modified sinc interpolation algorithm from reference [79] was used to improve timing resolution by providing sub-sample resolution for identifying pulse onset. Although this was not impactful for live detector data, high timing resolution was useful for time-tagged  $^{252}\text{Cf}$  calibrations used to accurately determine gamma and neutron population and timing. Pulses that occur between 2,000 ns preceding Event 39 up to 12,000 ns after are flagged that event should be blinded and are removed from analysis stream.

### 6.3.1 Detector Health Checks

In addition to the initial event processing, there are “health” checks on both detector performance and SNS operation to make a selection of what data will be included in the final

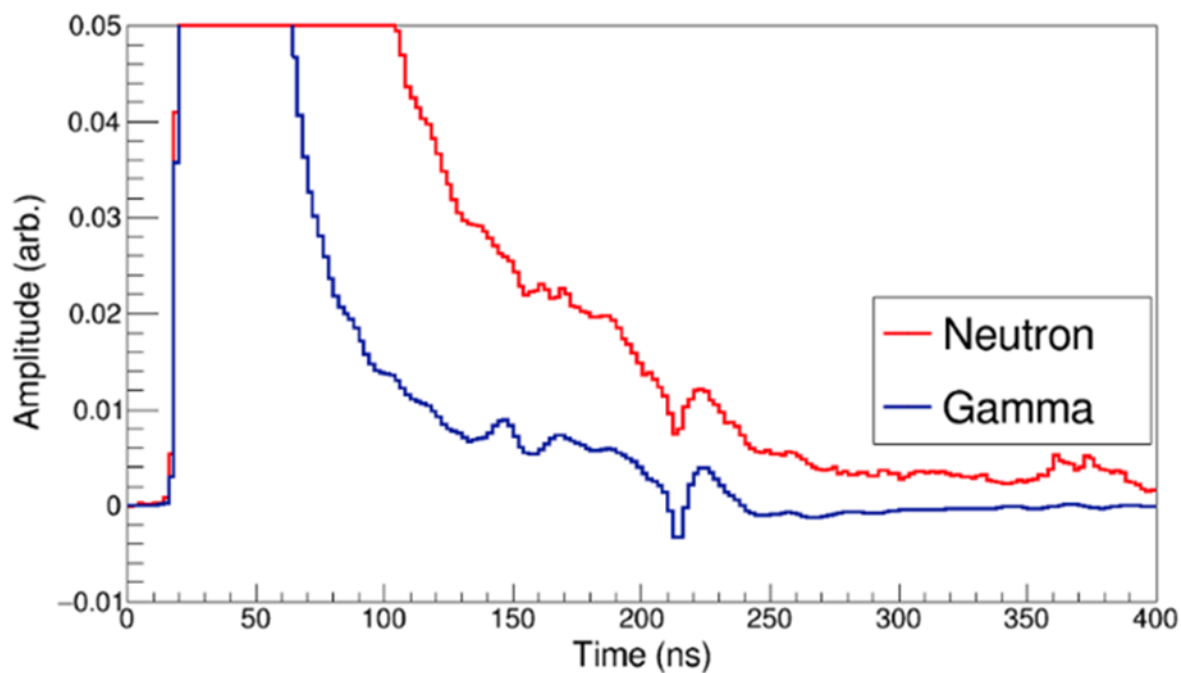


Figure 40. Average pulse shapes of neutrons and gammas for one channel, zoomed in near the baseline [70].

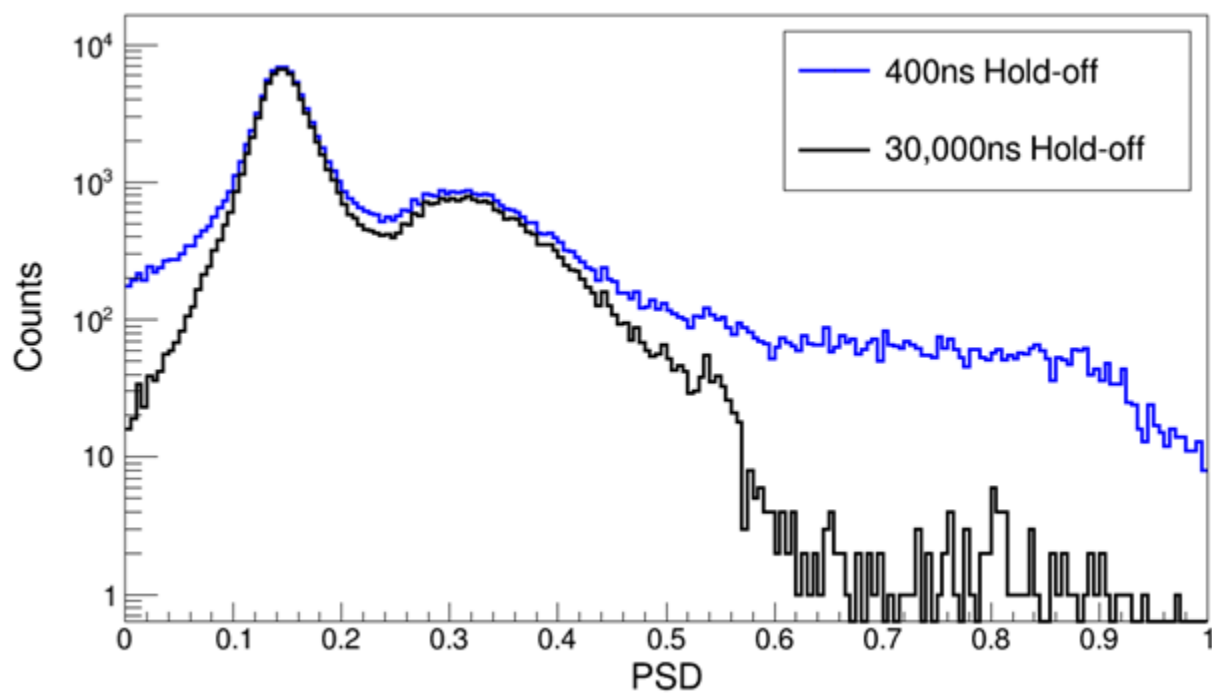


Figure 41. Effect of hold-off time on cleaning up "bad" PSD values and improving separation of neutron and gamma populations. In this plot, gammas have an average PSD value of  $\sim 0.15$  and neutrons  $\sim 0.45$ . Events falling outside of these populations are likely pile-up events [70].

analysis, which has been called the “Golden Run” list. For the liquid scintillator cells, requirements are imposed on a channel’s baseline, the variation of that channel’s baseline, the average variation of the samples used to calculate that baseline (referred to as baseline noise), and the variation of baseline noise throughout a run. This cut is to remove periods where electronics may be misbehaving and can change the energy resolution, PSD, and trigger rate of events. The criteria for this are listed in Table 5.

In addition to normal operation of the SNS, there are also periods where the SNS is being used for beam studies or tuning of the beam where beam power, proton energy and proton bunches differ from normal operation such that our predictions of neutrino flux which assume normal operating conditions, no longer hold. These runs are flagged and still used to track detector behavior over time but are eliminated in final data analysis. During normal SNS operations, there is requirement of beam power and beam energy to be close to full power, such that neutrino flux predictions hold. There were occasional issues with the muon veto PMTs, resulting in high event rates. This was typically caused by failure of components in the PMT bases. Runs during these periods would have large dead time due to high veto rate. The final exposure for each cell the resulting exposure after these data quality cuts (excluding SNS beam power and energy requirements) is listed in Table 6.

### 6.3.2 Muon Veto Cut

Cosmic muons can interact in the detectors as well as surrounding shielding and produce neutrons that can make their way into the liquid scintillator cells of the detector. Each muon veto panel, which surrounds the lead target on 5 sides, is equipped with 2 PMTs. To avoid triggering on non-cosmic background such as the 511 keV gamma rays from the nearby hot off-gas pipe that runs along Neutrino Alley, a coincidence of at least 2 veto panel PMTs within the width of the discriminator pulse ( $\sim 200$  ns) is required such that detector dead time is minimized and only cosmic muon events can cause this. Cosmic muons typically deposit enough energy that they are seen in two or more PMTs (if they pass through multiple panels) and the logical signal output from the veto discriminator unit is proportional to the number of PMTs firing, so the veto threshold is set with respect to the amplitude of the logical signal. The detector dead-time following a veto is determined by studying the timing and energy distribution of liquid scintillator events coincident to a muon veto event. One can see elevated activity in the detectors

Table 5. “Golden Run” criteria for neutrino cube run selection for final data set [70].

| Quantity                         | Requirement          | Runs Eliminated              |
|----------------------------------|----------------------|------------------------------|
| Liquid Scintillator Requirements |                      |                              |
| Baseline variation over run      | $\leq 20$ ADC        | Large variations in baseline |
| Average baseline noise           | $\leq 5$ ADC         | High noise                   |
| Average baseline noise variation | $\leq 1$ ADC         | Large variation in noise     |
| Detector Trigger rate            | $\leq 20$ Hz         | Triggers malfunctioning      |
| Liquid scintillator event rate   | $\leq 0.5$ Hz        | High backgrounds             |
| Baseline                         | $\leq 16100$ ADC cut | Baseline saturation          |
| SNS Requirements                 |                      |                              |
| Average beam power               | $\geq 0.8$ MW        | SNS tuning run               |
| Average beam energy              | $\geq 900$ MeV       | SNS tuning run               |
| Muon Veto Requirements           |                      |                              |
| 2+ Veto PMT Rate                 | $\leq 800$ Hz        | High muon dead time          |

Table 6. Final exposure for each liquid scintillator channel (detector) deployed in the lead neutrino cube in final data set [70].

| Channel | Total Exposure [Days] | Beam Exposure [GWHr] |
|---------|-----------------------|----------------------|
| 0       | 178.2                 | 2.553                |
| 1       | 1281.4                | 19.433               |
| 2       | 1158.5                | 17.641               |
| 3       | 178.3                 | 2.554                |
| 12      | 482.4                 | 7.391                |
| 13      | 889.8                 | 13.228               |

for some time following an event in the muon veto panel (Figure 42). Based on this study, events in the liquid scintillator within a window of  $[-200 \text{ ns}, 25000 \text{ ns}]$  with two or more veto PMT signals above threshold are tagged as a cosmic muon event. The effect of this cut on detector efficiency is shown in Table 7.

High energy electrons produced in charged-current neutrino interactions can possibly exit the lead and interact in the veto panel. Determining the impact of this process on detector dead-time is difficult due to imprecise knowledge of the exact value of the muon veto PMT thresholds and non-uniformity of the panels' light transmission. To estimate the possible effect of this, an MCNP simulation was run with 100,000 electrons originating in the lead with an energy spectrum calculated for charged-current neutrino events on lead for single neutron emission with a stopped-pion electron neutrino energy spectrum. The threshold of the muon vetoes was varied between 500 keV to 5 MeV and the resulting efficiencies are shown in Table 8. The actual threshold of the muon vetoes is assumed to be  $\sim 2 \text{ MeV}$  and the uncertainty of this value's effect on efficiency is determined by this simulation. Overall, both muon veto dead-time and dead-time from electrons produced by charged-current neutrino interactions result in a few percent decrease in efficiency.

## 6.4 Detector Characterization

### 6.4.1 Energy Calibration

The energy calibration was determined through multiple methods. Gamma source calibrations were done several times throughout the detector's lifetime, typically during times of no beam activity, to fit energy resolution parameters and determine absolute energy scaling for each channel. To track gain changes of PMTs on shorter timescale, background events from  $^{40}\text{K}$  in PMT tubes were studied in detector data. Light output in liquid scintillators is linear above  $\sim 40 \text{ keV}$  [80]. The energy of light output can be described by the equation:

$$L = c(E_e - E_0) \quad (5.1)$$

where  $L$  is the light output,  $c$  is a conversion constant,  $E_e$  is true energy in keV and  $E_0$  is a small offset to account for non-linearity at low energy. Gamma lines are often seen by their Compton edge rather than by their peak energy. The location of the Compton Edge can be described by the equation:

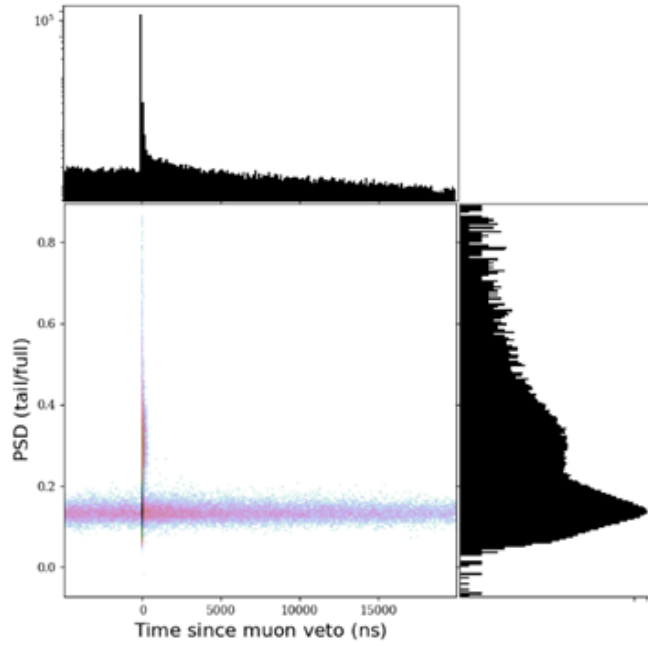


Figure 42. Time to the muon veto signal ( $t=0$ ) for liquid scintillators vs. PSD [70].

Table 7. Efficiency of muon veto cut [70].

| Channel | Efficiency |
|---------|------------|
| 0       | 0.993      |
| 1       | 0.995      |
| 2       | 0.995      |
| 3       | 0.998      |
| 12      | 0.997      |
| 13      | 0.997      |

Table 8. Muon veto threshold vs. percentage of simulated charged-current events vetoed [70].

| Threshold [MeV] | Events veto'd [%] |
|-----------------|-------------------|
| 0.5             | 1.915             |
| 1.0             | 1.902             |
| 1.5             | 1.882             |
| 2.0             | 1.852             |
| 3.0             | 1.780             |
| 4.0             | 1.721             |
| 5.0             | 1.557             |

$$E_c = \frac{2E_\gamma^2}{m_e + 2E_\gamma} \quad (5.2)$$

where  $E_c$  is estimated as half the value from maximum value of Compton edge to the half-max [81]. Energy resolution will affect the exact location of  $E_c$  so the following approach was developed for determination of these parameters. Gamma source calibrations were repeated in simulation and then scaled like Equation 5.1 after they were first smeared the response with energy-dependent resolution parameters of the form:

$$\frac{\Delta E}{E} = \sqrt{\alpha^2 + \frac{\beta^2}{E} + \frac{\gamma^2}{E^2}} \quad (5.3)$$

where  $\Delta E$  is the FWHM of a gaussian centered at  $E$  and  $\alpha$ ,  $\beta$ , and  $\gamma$  are resolution parameters originating from different aspects of signal production.  $\alpha$  is due to the location-dependent light transmission of scintillation to the photocathode.  $\beta$  arises the statistical nature of light production, attenuation, conversion to electrons then amplification in the PMT.  $\gamma$  is from noise from dark counts in PMT and from amplification.

Gamma source calibrations were repeated in MCNP [82], replicating the source location and detector geometry. The best fit parameters for each channel were not initially known and parameters were allowed to float. Emcee [83], a Python based Markov-Chain Monte Carlo ensemble sampler, was used to sample the resolution and calibration parameter space, and RooFit [84] was used to calculate log-likelihood functions for each set of parameters. Probability Distribution Functions (PDF) were generated for calibration data, background data (no source) and simulated detector response (Figure 43). The resolution and scaling parameter space was sampled with emcee and applied to the simulated detector response which was then added to anappropriately scaled background PDF then the negative log-likelihood was calculated for this set of parameters. The best-fit energy scale factors and energy resolution parameters are shown in Tables 9 and 10 respectively.

While the gain can be determined at the time of calibration, the value of ADC-to-keV conversion was observed to change over time. This could be due to aging of the PMT, oxygen leaking into the scintillator, helium leaking into the PMT, or change in temperature. To account for the change in gain over time, a procedure was developed to fit the current run's background spectrum from  $^{40}\text{K}$  gamma rays to determine the change in the ADC-keV conversion parameter

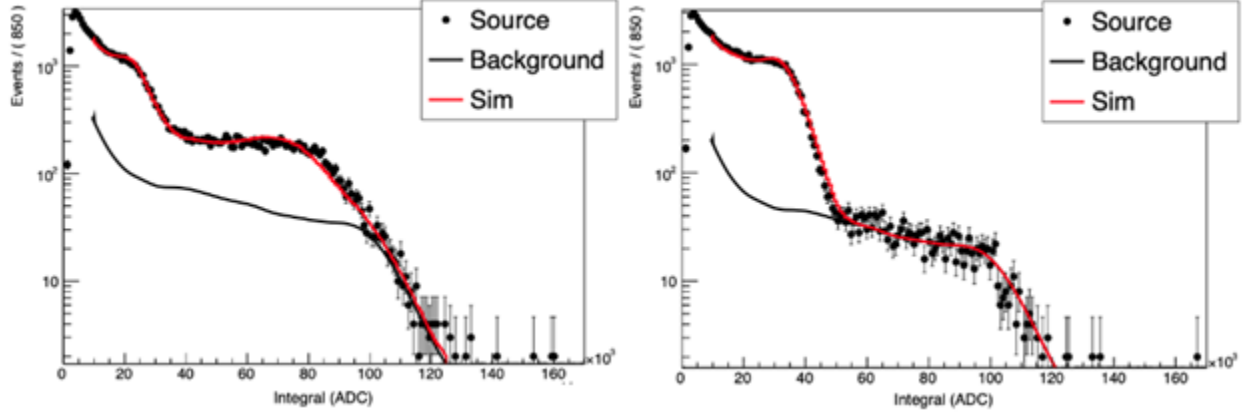


Figure 43. (Left)  $^{22}\text{Na}$  calibration and (Right)  $^{137}\text{Cs}$  calibration for single detector [70].

Table 9. Energy scaling factor for lead neutrino cube liquid scintillator channels [70].

| Lead Neutrino Cube |                      |
|--------------------|----------------------|
| Channel            | Scaling [ADC/keV]    |
| 0                  | $60.0^{+0.7}_{-0.7}$ |
| 1                  | $63.1^{+2.5}_{-2.5}$ |
| 2                  | $52.1^{+0.7}_{-0.7}$ |
| 3                  | $51.7^{+0.5}_{-0.6}$ |
| 12                 | $68.4^{+2.6}_{-2.6}$ |
| 13                 | $63.0^{+2.8}_{-2.8}$ |

Table 10. Energy resolution parameters for lead neutrino cube liquid scintillator channels [70].

| Channel | Alpha [unit-less]         | Beta [ $\sqrt{\text{keV}}$ ] | Gamma [keV]                 |
|---------|---------------------------|------------------------------|-----------------------------|
| 0       | $0.101^{+0.004}_{-0.004}$ | $0.356^{+0.213}_{-0.210}$    | $4.543^{+2.451}_{-2.464}$   |
| 1       | $0.102^{+0.004}_{-0.004}$ | $0.794^{+0.473}_{-0.398}$    | $12.565^{+4.587}_{-4.998}$  |
| 2       | $0.093^{+0.021}_{-0.006}$ | $0.668^{+0.404}_{-0.328}$    | $11.890^{+12.993}_{-4.464}$ |
| 3       | $0.093^{+0.008}_{-0.008}$ | $1.584^{+0.238}_{-0.316}$    | $13.222^{+4.093}_{-4.791}$  |
| 12      | $0.071^{+0.013}_{-0.011}$ | $0.793^{+0.147}_{-0.243}$    | $11.810^{+2.382}_{-3.041}$  |
| 13      | $0.069^{+0.005}_{-0.005}$ | $0.519^{+0.205}_{-0.255}$    | $6.910^{+2.929}_{-3.297}$   |

for a given run period. The high energy region of the detector's background spectrum is fit with a RooKeysPDF every ninety-six-hour interval of detector operation. The gain correction factor from each ninety-six-hour period is then compared to known ADC-to-keV conversions obtained from gamma source calibrations to determine a scale factor for each run period (Figure 44).

## 6.4.2 Threshold Determination

Nuclear recoils are highly quenched and produce less visible light than electronic recoils for the same deposited energy. Considering the shape and energy of the neutrino-induced neutron spectrum, the location of threshold could greatly impact the observed event rate, as many of these recoils will produce be roughly on the order of 100 keVee. The first correction is to account for the change in baseline over time. Scintillation light reaching the PMT produces a current proportional to the amount of light yield and the analog electrical signal of the PMT is read by the Analog-to-Digital Converter (CAEN1730) and digitized for consequent trigger logic and storage. The hardware trigger threshold is set to  $\sim 200$  ADC units above the baseline, but this value can change as baseline value drifts over the course of operation. A secondary software threshold was developed for each detector to simplify analysis with a single threshold (for each detector) for the final data set. The procedure is as follows:

1. For each run, the baseline sample with the greatest difference from hardware trigger level is found. All events with an amplitude greater than this value surpass the hardware trigger.
2. These amplitudes are added to a histogram: the secondary threshold is chosen such that its value minimized while accepting as much data as possible.
3. If the software threshold is greater than the absolute hardware threshold, the run is excluded from analysis, eliminating runs where the hardware trigger was not sensitive to low energy events.
4. For runs that pass this cut, any event with amplitude less than the secondary threshold is removed, resulting in a single common threshold for data analysis.

The secondary software thresholds used in analysis of final data set are listed in Table 11.

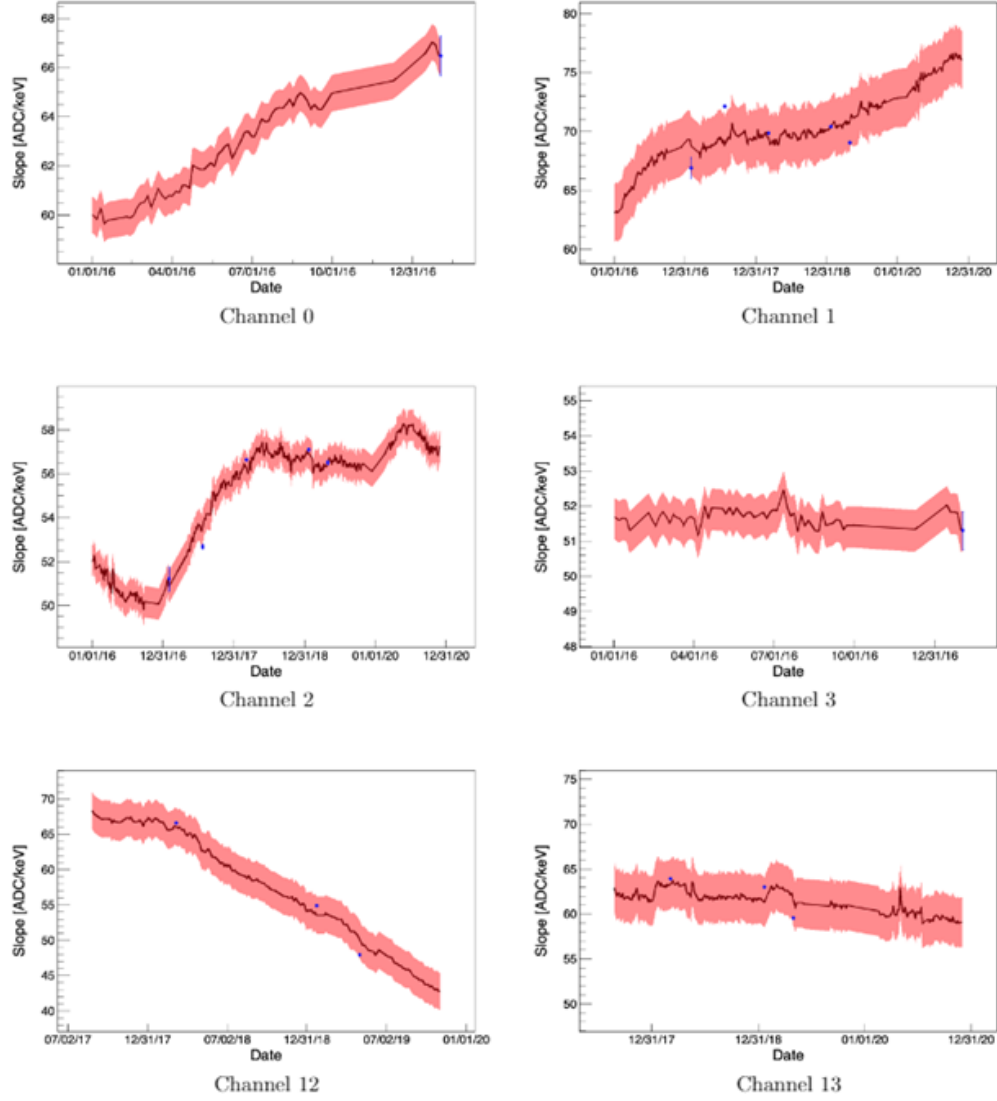


Figure 44. Gain drift of liquid scintillator cells of the lead detector. Gamma source calibration points are in blue [70].

Table 11. Calculated secondary software thresholds [70].

| Lead Neutrino Cube |                           |
|--------------------|---------------------------|
| Channel            | Secondary Threshold [ADC] |
| 0                  | 215                       |
| 1                  | 222                       |
| 2                  | 234                       |
| 3                  | 210                       |
| 12                 | 237                       |
| 13                 | 241                       |

### 6.4.3 Time-Tagged $^{252}\text{Cf}$ Neutron Calibration

Prior to installation in Neutrino Alley, neutron calibrations had been done at TUNL for the cylindrical Eljen cells. However, the data calibration was lost due to accidental deletion during maintenance of the computing cluster where this data had been stored. An in-situ time-tagged  $^{252}\text{Cf}$  calibration run was used to recreate a high statistics population of gammas and neutrons to study detector performance. Additionally, doing this calibration with the completed detector assembly and deployed electronics provides more accurate determination of detector performance. The neutrons produced in  $^{252}\text{Cf}$  have an average energy close to the expected energy for BRNs and NINs (Figure 47) and can be used for threshold determination of nuclear recoils. The time-tagged  $^{252}\text{Cf}$  source is composed of a  $^{252}\text{Cf}$  source in an ionization chamber that can detect when a fission occurs, and this produces a signal that can be used for neutron timing information or energy reconstruction [85]. A schematic of the  $^{252}\text{Cf}$  fission chamber is shown in Figure 45. For the calibration run, the timing signal of the fission chamber replaces the SNS timing signal Event 39 so the data acquisition can be operated with the same trigger conditions of coincidence. Neutrons travel less than the speed of light and are delayed relative to gammas due to difference in their time-of-flight. From this they are easily identified (Figure 46). A thirty-nanosecond window was used for obtaining gammas and a three-hundred nanosecond window for neutrons. The detector will typically only see either a gamma or a neutron. A simple box cut in time-PSD space around these populations yields a ratio of  $\sim 1.5$  gammas per neutron, which is in good agreement with the findings in Ref [86].

Although there is a set signal amplitude threshold, a single value of amplitude applies to a range of values for integral, and visa-versa. To determine the threshold function – the trigger efficiency given certain integral, the conversion from peak height to integral space should be determined. Additionally, nuclear recoils have more light in the tail fraction of the integral, which relates to a lower peak amplitude to integral ratio than electronic recoils whose scintillation is more prompt (Figure 48). Therefore, the threshold function will be different for neutrons and gammas. For each liquid scintillator channel, the ratio of peak height to integral as a function of energy are plotted for both populations. 500 ADC slices are taken along integral axis and the peak amplitude distributions are plotted and fit with Gaussian. At this point, the secondary software threshold is applied to account for baseline drift, and its value is chosen such

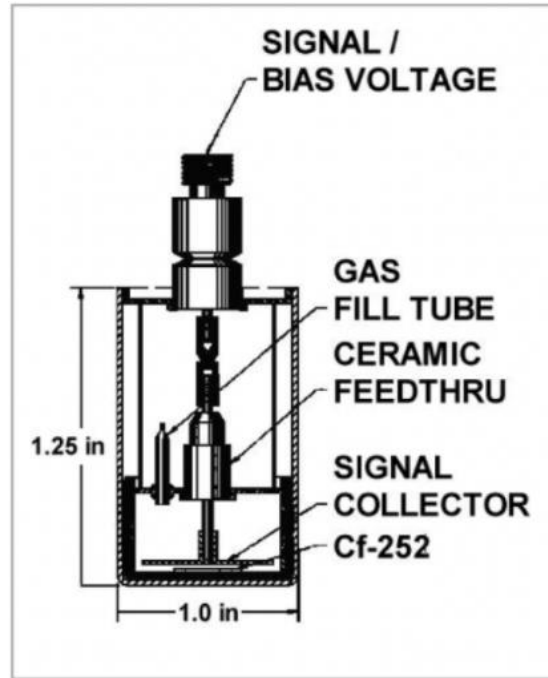


Figure 45. Schematic of  $^{252}\text{Cf}$  fission chamber.

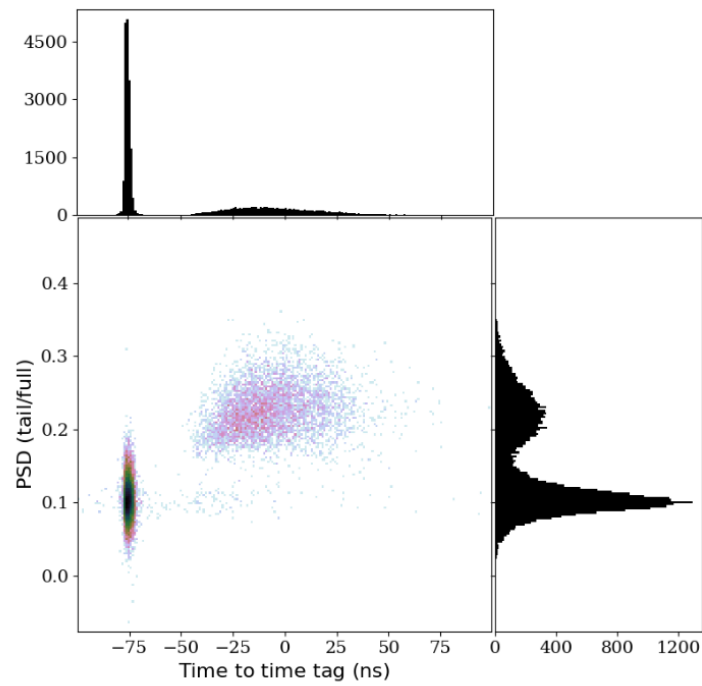


Figure 46. Time to the time tag vs. PSD of events. Gammas appear first at  $t = -75$  ns and neutrons appear later between  $t = -50$  ns to  $t = +50$  ns. Gamma flash was used to calibrate the time delays in cables and PMTs [70].

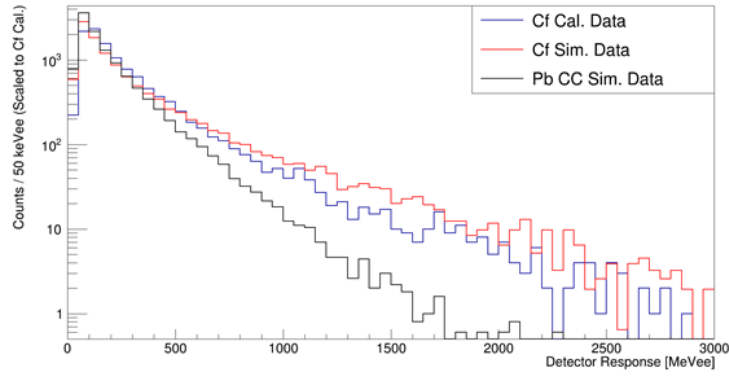


Figure 47. Simulated detector response of neutrons produced from charged-current neutrino interactions in Pb (black) using Ref. [2] compared with the  $^{252}\text{Cf}$  calibration data (blue) and  $^{252}\text{Cf}$  simulation data (red) for a single channel. Simulations are scaled to  $^{252}\text{Cf}$  calibration data. Neutrons from  $\text{Cf}^{252}$  calibration is taken from simple box cut in time-PSD space as seen in Fig 51. Discrepancy near threshold could be due to run-dependent baseline variation that is unaccounted for in this calibration run [70].

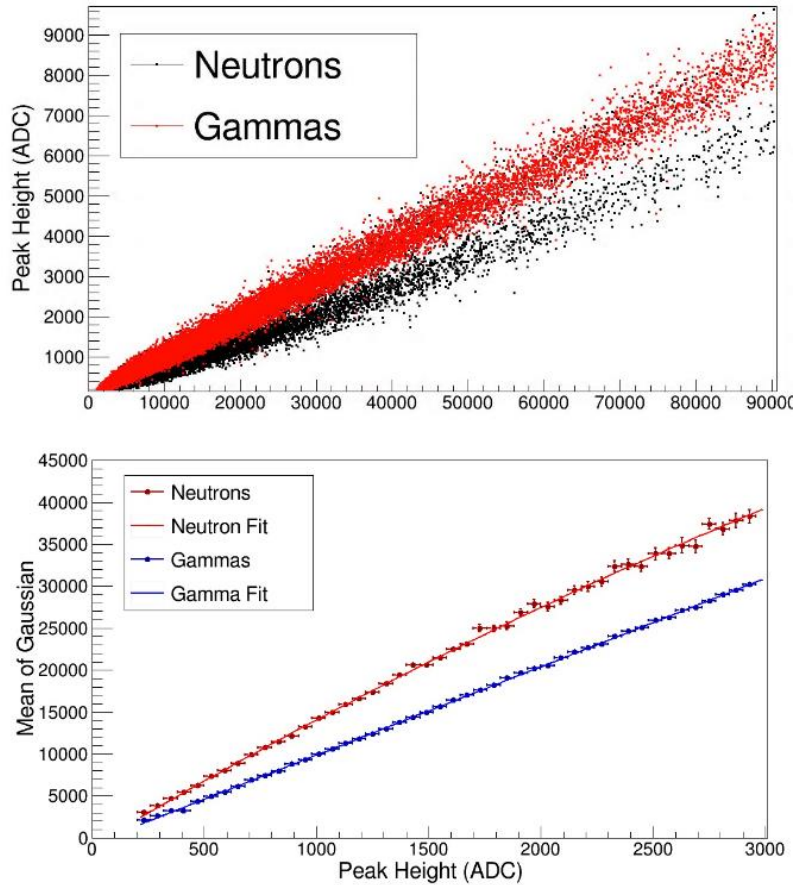


Figure 48. (Top) Ratio of peak amplitude to total integral for neutrons and gammas from  $^{252}\text{Cf}$  calibration. Neutrons and gammas are separated by time-of-flight (Figure 46) and (Bottom) the mean integral of each population versus the peak amplitude. The distribution of peak height for each slice in integral space is used for determining the threshold efficiency curves in Figure 48 [70].

that all pulses identified by the software trigger will always be tagged by the hardware trigger (regardless of some change of baseline). The final threshold efficiency curve (Figure 49) is created from choice of the secondary threshold (Table 11) and the peak height distributions (Figure 48). For each integral value, the percentage of amplitudes greater than the secondary threshold is calculated. Then the threshold is converted to keV from the run-dependent ADC-to-keV scale factor. Then the curve is weighted by beam exposure of this run and the curves for each run are added together for a final threshold efficiency curve that is valid for the final data set.

#### 6.4.4 PSD Correction

The in-situ neutron calibration with a  $^{252}\text{Cf}$  source were used to study detector response to neutrons. However, it was observed that the PSD distributions of neutrons and gammas from these calibrations did not match the PSD distributions of the full data set. This could be due to change of PMT behavior during high event rate of neutron source runs, aging of the PMT, leakage of oxygen into the scintillator, or leakage of helium into the PMT. As is usual for neutrino experiments, data was taken over the course of several years (January 2016 – August 2020) to acquire sufficient statistics. The large gamma background provided sufficient statistics to study the time dependence of the gamma pulse shape distribution (Figure 50) and a procedure was developed to correct for this. The neutron background was significantly lower, preventing the use of detector data to directly determine the shift of PSD for this population, but the same relative shift in PSD distribution was observed. Also, this shift did not appear to have energy dependence. The data set was broken up into sets of a fixed number of events (25,000) and the gamma mean was fit. The distribution was shifted with a scaling factor to enforce that the mean of the gamma PSD = 0.1, resulting in a decrease of FWHM/ $\mu$  and better separation of neutrons and gammas.

#### 6.4.5 PSD Fitting

The same PSD correction was applied to neutron calibrations. Even after this correction, there was still an observable discrepancy between the PSD of neutron calibrations and background data. The low rate of background neutrons in the live data made fitting PSD distributions with background data alone difficult. In liquid scintillators, gamma and neutron

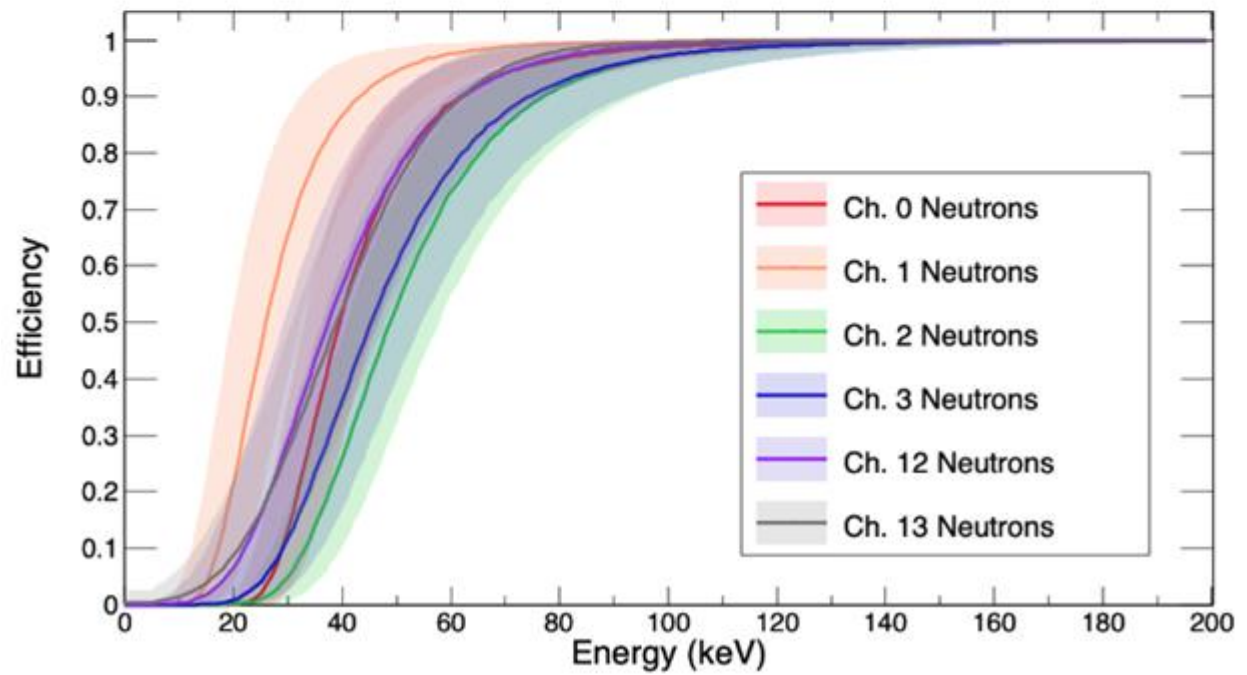
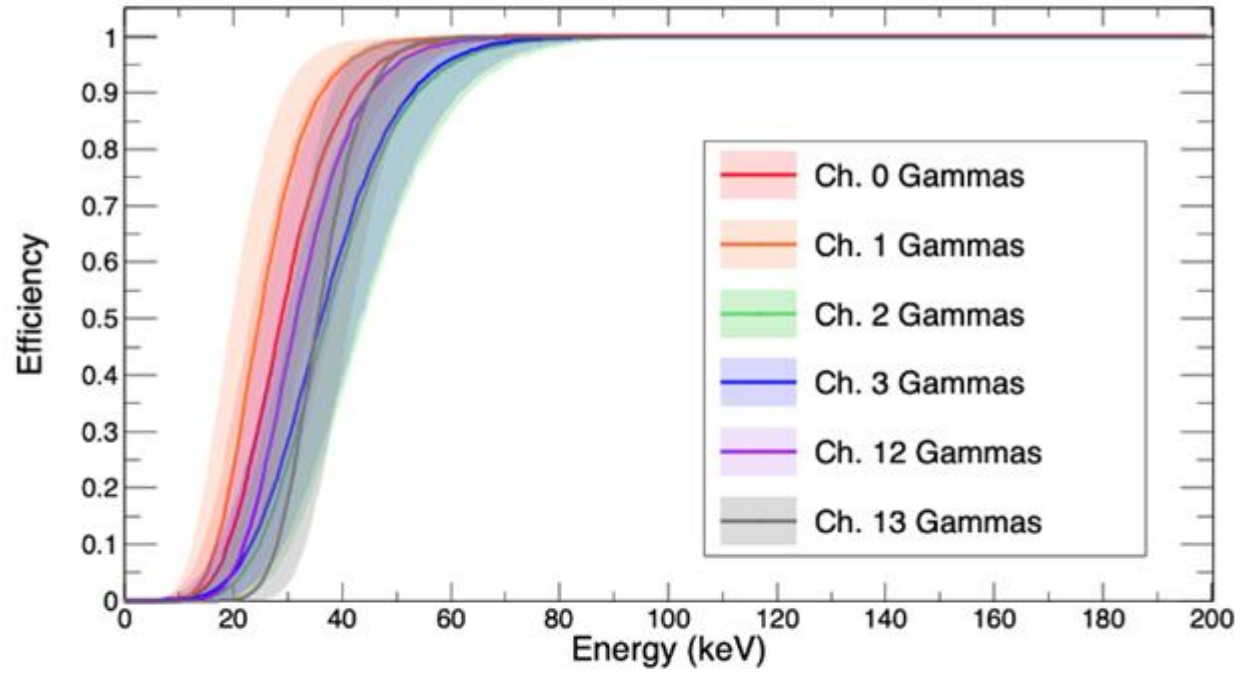


Figure 49. Threshold Efficiency for gammas (top) and neutrons (bottom) in the Pb Neutrino cube [70].

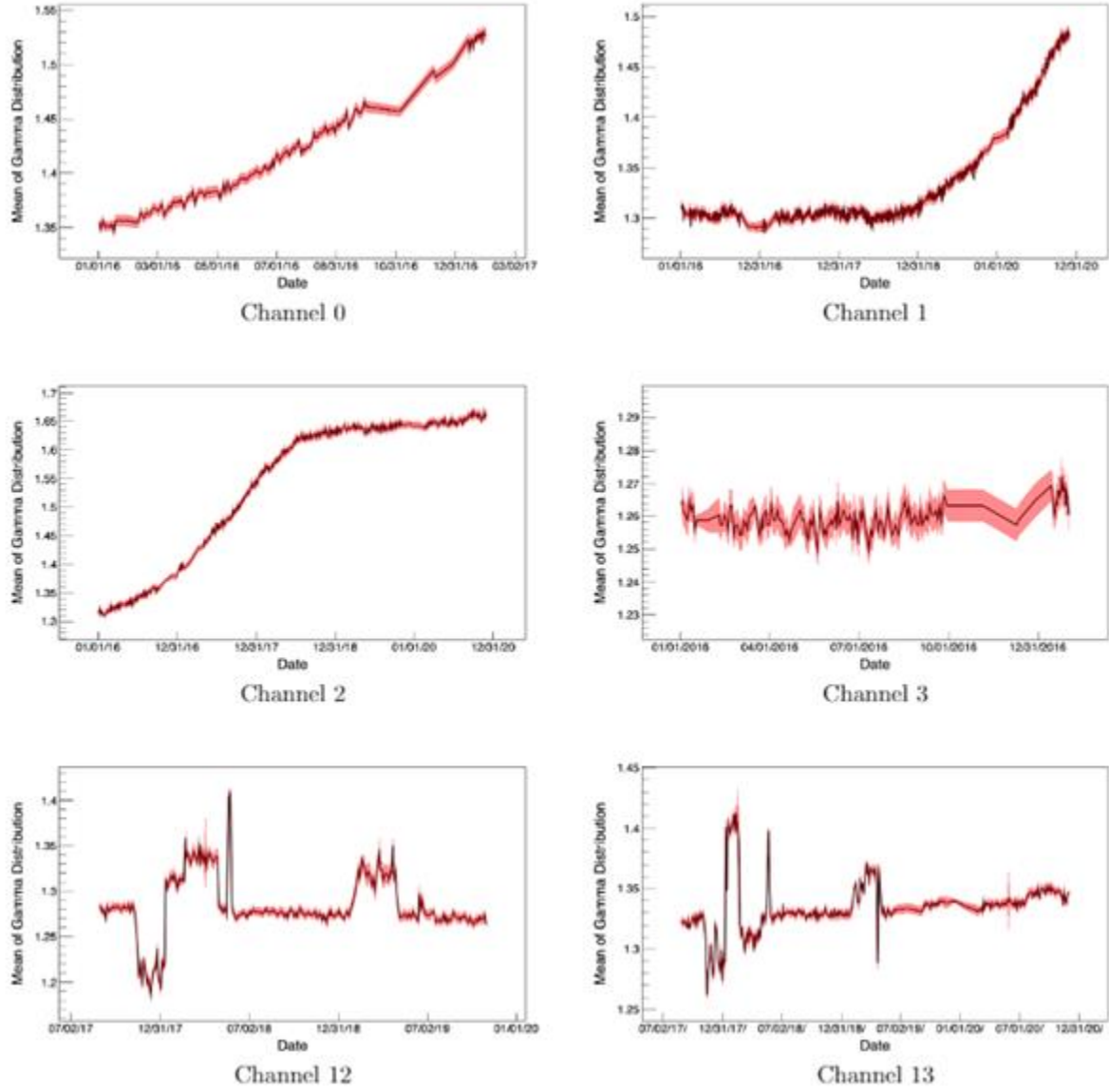


Figure 50. Mean of gamma PSD distribution (uncorrected) over time for lead detector channels [70].

PSD distributions are described by a gaussian convolved with an exponential decay (RooDecay in RooFit) giving three parameters, mean, sigma, and a decay constant. The PSD distribution from the  $^{252}\text{Cf}$  data for both gammas and neutrons were selected in 25 keV slices and fit with RooDecay function allowing parameters to fit. The means were observed to be of the form:

$$f(E) = mE + b, \quad (5.4)$$

and for the sigmas and decay parameters:

$$f(E) = \frac{c}{\sqrt{E}}. \quad (5.5)$$

The coefficients of these functions were then allowed to float in a simultaneous fit to the PSD distributions of all energy slices between  $\sim 100$  keV to  $\sim 1200$  keV. This procedure was used again for the background data set, allowing the coefficients to float, and obtaining a set of functions that characterize the PSD energy dependence for each detector. Next, the optimal energy range was determined based on PSD parameters and expected signal and expected background. The threshold above which PSD distributions are valid is affected by the presence of low energy Cherenkov events and pile-up events and varies by detector. Each energy slice was stepped over in PSD slices of width 0.0005 such that the signal and background above each PSD slice is calculated, optimizing sensitivity of  $\frac{s}{\sqrt{s+b}}$ . The optimal PSD cut is then used to calculate the neutron and gamma acceptance efficiency of this PSD cut. The PSD distributions and optimal PSD cut are shown in Figure 51.

## 6.5 Signal Prediction

### 6.5.1 Neutrino-Induced-Neutron Signal Generation

Events from the neutrino interaction simulation package, MARLEY [65], were used as input in GEANT4 as an event tree for sampling using ROOT software package (Figure 52). The spectrum calculated by Ref. [2] can be put into an event tree of similar form, although the 1 neutron to 2 neutron ratio is decided by their respective cross-sections calculated from supernova neutrino energy spectra. Resulting neutron spectra from MARLEY is shown in Figure 53 (compare to Ref [2], Figure 33). The resulting neutron energy spectra provided in this reference combines the two decay channels without information of their contributions. Additionally, 3 neutron emission is possible and accounted for in MARLEY. The simulation output is a root

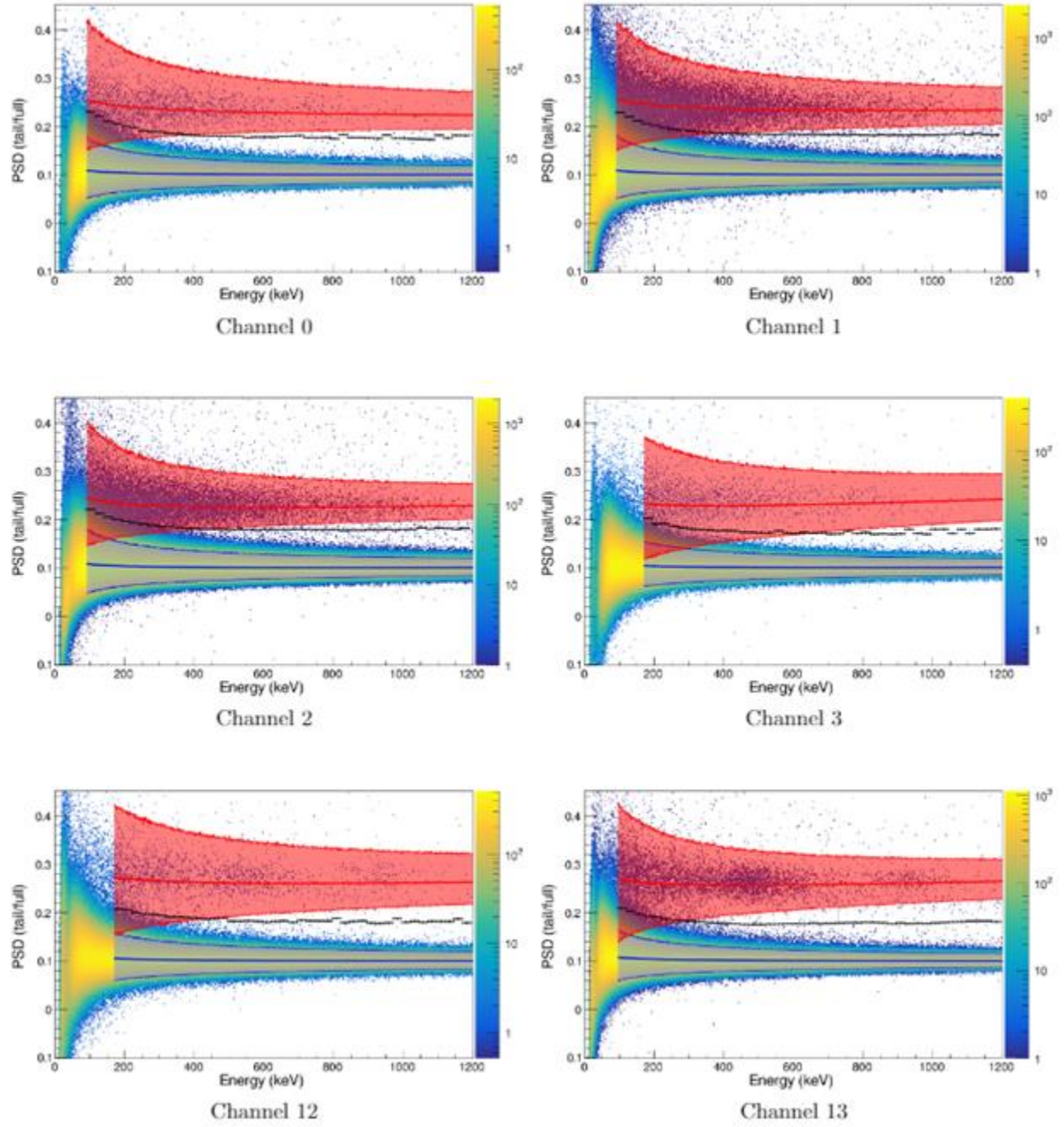


Figure 51. Energy-PSD distributions of background data for lead neutrino cube detectors. (Red) Nuclear recoil band and (Blue) Electron recoil band. The black line marks the optimal PSD cut for each channel [70].

# MARLEY Event Generator

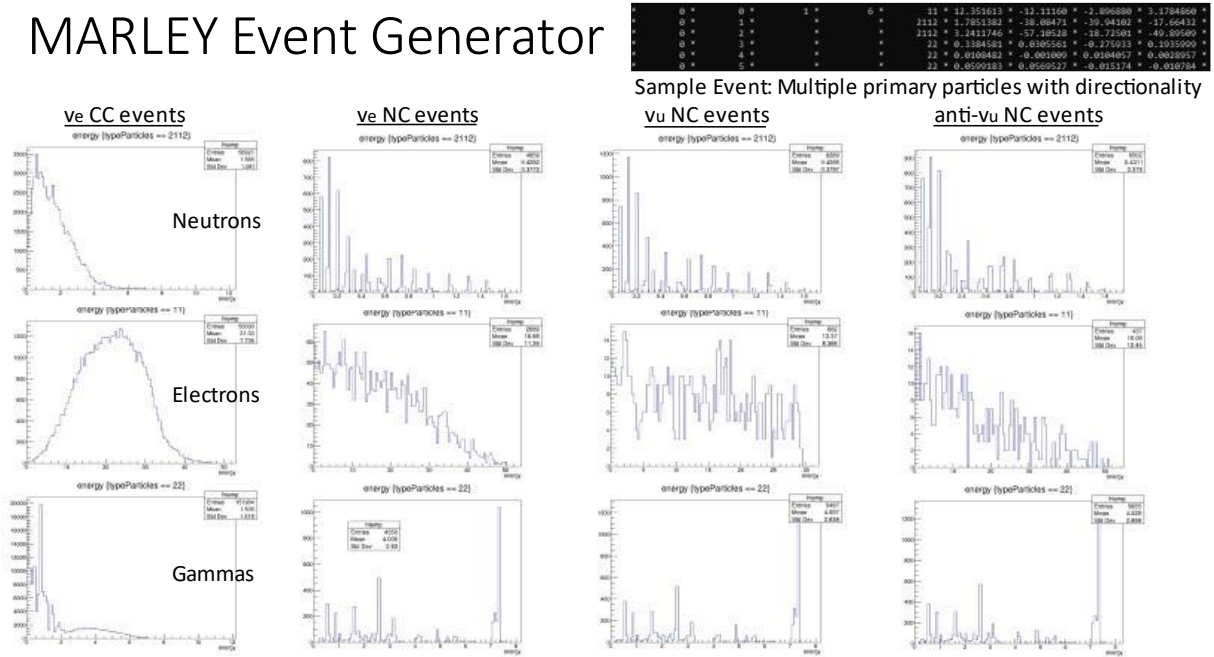


Figure 52. MARLEY event distributions to be used as input for simulations in Neutrino Cube. (Top Right) example of multi-particle event input.

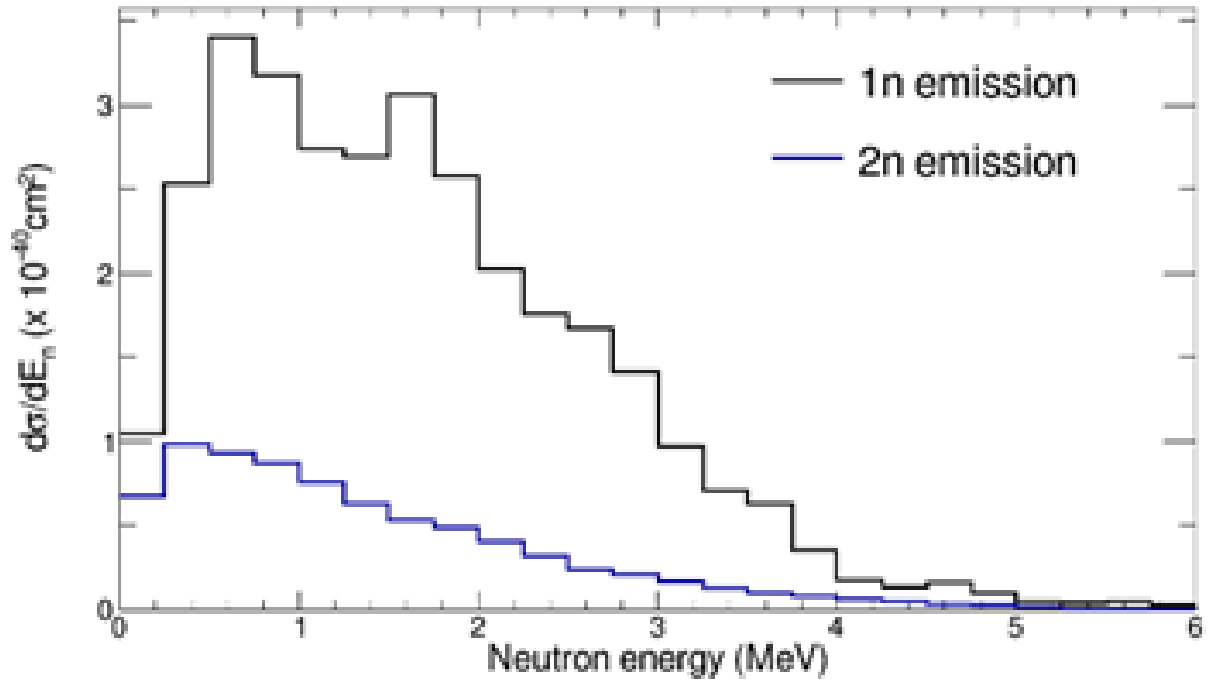


Figure 53. Comparison of 1n and 2n for charged-current neutron production cross-section for pion decay-at-rest in MARLEY [70].

event tree that includes particle track identification, particle type, and the time and energy of each interaction vertex. This output design allows for quenching of neutron signal in detector to be accurately handled in a post-processing root script as the individual hits are accumulated into events, as well as using particle type as a proxy for pulse shape identification and anticipating possible event contamination. Especially since MARLEY allows one to also model the charged lepton that can lead to the event being vetoed or misidentified. Similar to the procedure for calibrations, Monte Carlo data generated using a GEANT4 simulation package has energy resolution, scaling, and thresholds applied to construct the signal PDFs to be used for fitting.

## 6.5.2 Beam-Related Neutron Studies

Beam related neutrons (BRN) produce a non-negligible background for all COHERENT detectors. These, like NINs, arrive in time with proton beam on target beam activity and therefore cannot be reduced using the pulsed nature of the SNS. Furthermore, the amount of shielding between the target and detectors in Neutrino Alley varies by location, so the background contribution for each detector from BRNs varies corresponding to this. There are many attenuation lengths of material between the target and neutrino alley such that it would be computationally unfeasible to simulate enough events from the SNS target to see any events in the detector. Uncertainties in the neutron interaction cross-section make it impossible to predict neutron rates with reasonable accuracy. The approach we take to understand this background begins with some basic assumptions on how the BRNs are reaching Neutrino Alley to computationally simplify the BRN model, then compare this model to detector data to reconstruct the incident flux.

The initial neutron spectrum from the target is known to a good degree from existing measurements of  $p+^{208}\text{Pb}$  scattering [87] (Figure 55). We assume that high energy neutrons from proton interaction on lead are very similar to interactions on the mercury. The Lead Neutrino Cube, whose position in the hallway is nearest the target, sits at a location  $\sim 90^\circ$  from the mercury target at approximately 20 meters away from the target located at C5 location shown in Figure 54. Between the target and Neutrino Alley exists a combination of 5 meters of the steel monolith surrounding the target and then concrete for the remainder of the 20-meter distance to the

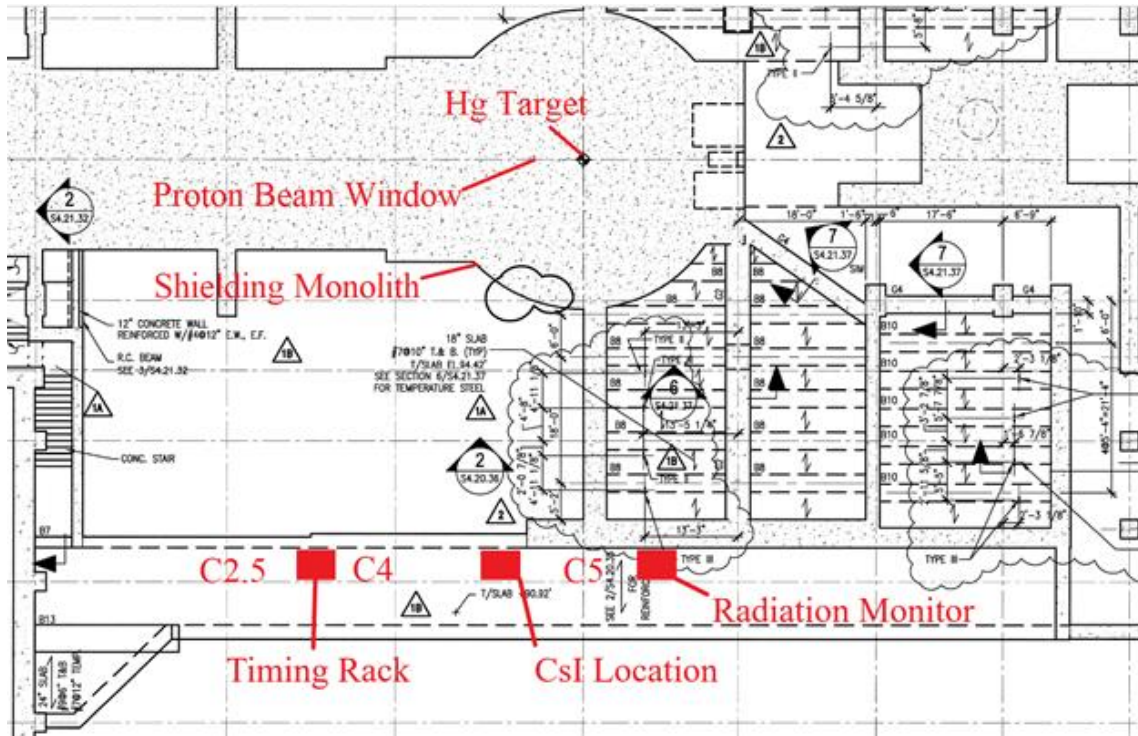


Figure 54. Top-down schematic of Neutrino Alley and shielding surrounding the SNS Target below the SNS experiment hall. C4 is the location of the former CsI detector. About 2 meters to the right of C4 is the location of the Lead Neutrino Cube.

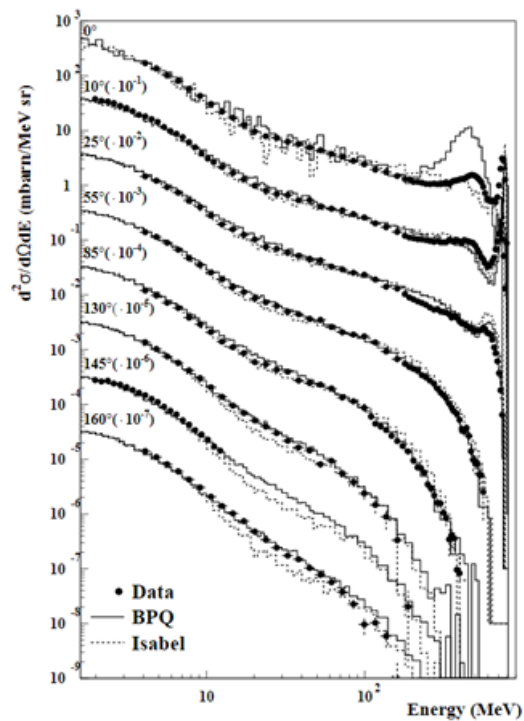


Figure 55. Neutron Energy Spectrum for 800 MeV protons incident on  $^{208}\text{Pb}$  for various angles

detector location. Compared with the target floor, the flux and time spread of the BRN flux is greatly reduced by this additional concrete between the Neutrino Alley and the main experiment floor (shown in Figure 29). The steel and concrete shielding correspond approximately to more than 30 meters of solid concrete equivalent.

The neutron spectrum for  $85^\circ$   $p+^{208}\text{Pb}$  scattering data is convolved with the attenuation of primary neutrons for this amount of shielding and results in a most probable neutron energy penetrating this shielding of  $\sim 400$  MeV. For such high energy neutrons, the spread in arrival time relative to the beam profile is small, on the order of 10s of ns (Figure 56), leading to our initial conclusion that these BRNs are taking a direct path through the shielding to the detector. Neutrons which do not interact in the shielding and retain their energy, are likely to pass through the detectors. However, those which have some interaction in the massive concrete structures near the Neutrino Alley wall will produce secondary neutrons of low enough energy to potentially be seen in the detectors because cross-section of low energy neutrons is much higher than for 400 MeV neutrons. To model this, we begin with a mono-energetic neutron flux generated in a plane shadowing the Neutrino Cube from 1 meter deep in the concrete, directed towards the wall (See GEANT4 Event Display in Figure 57). Since the detectable neutrons will be result of some elastic and inelastic interactions and have their directions randomized, this is a good approximation for characterizing the BRNs reaching this location. To validate the robustness of this model (in the case of a different number of attenuation lengths, different beam energy, different target), we compare simulations of varying initial depth in concrete (Figure 58) and varying initial neutron energy (Figure 59). Other than in the case of very shallow ( $< 50$  cm) depths for initial position, the choice of initial conditions leads to congruent spectra that differ only by normalization. The most impactful difference to simulated BRN spectra is choice of concrete, which distorts the low energy ( $< 20$  MeV) region of the BRN spectrum for the SNS concrete compared to Geant4 default concrete material definition (Figure 60). The concrete definition slightly differs in density and composition from the standard GEANT4 material definition, but from study of the influence of depth vs. resulting spectrum, we conclude it is the composition responsible for this difference and choose the SNS concrete composition for simulating BRNs.

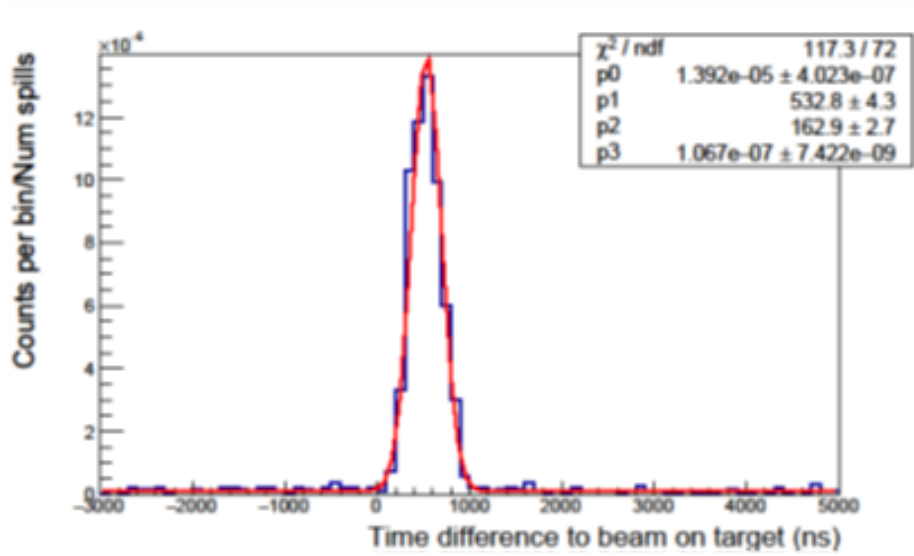


Figure 56. Neutron Timing Cart measurement taken at location in front of Radiation Monitor (without lead shielding). Results indicate a 162.9 ns sigma, consistent with the beam width of 161.4 ns sigma within error.

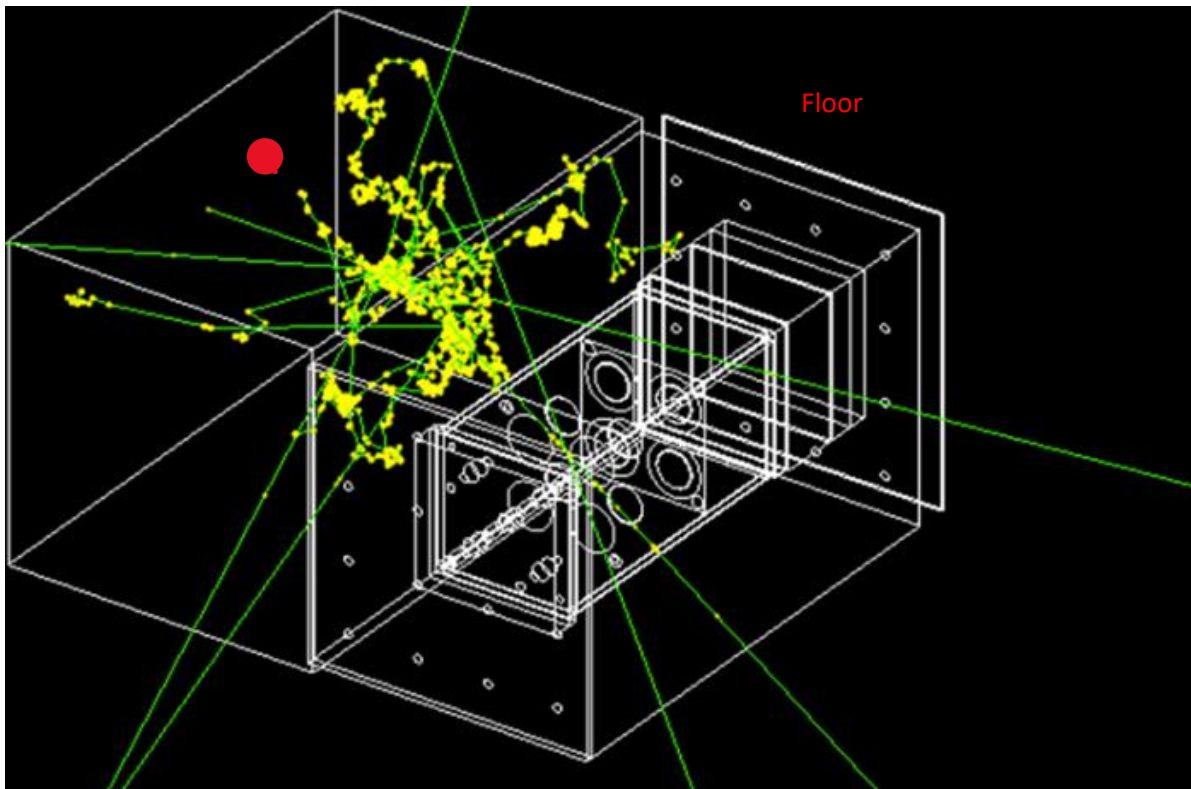


Figure 57. Wireframe graphic of Geant4 BRN event resulting in a detectable neutron in a liquid scintillator cell in the Lead Neutrino Cube (image is on its side, floor is right most plane facing into page). Origin of primary 400 MeV neutron is marked by the red dot.

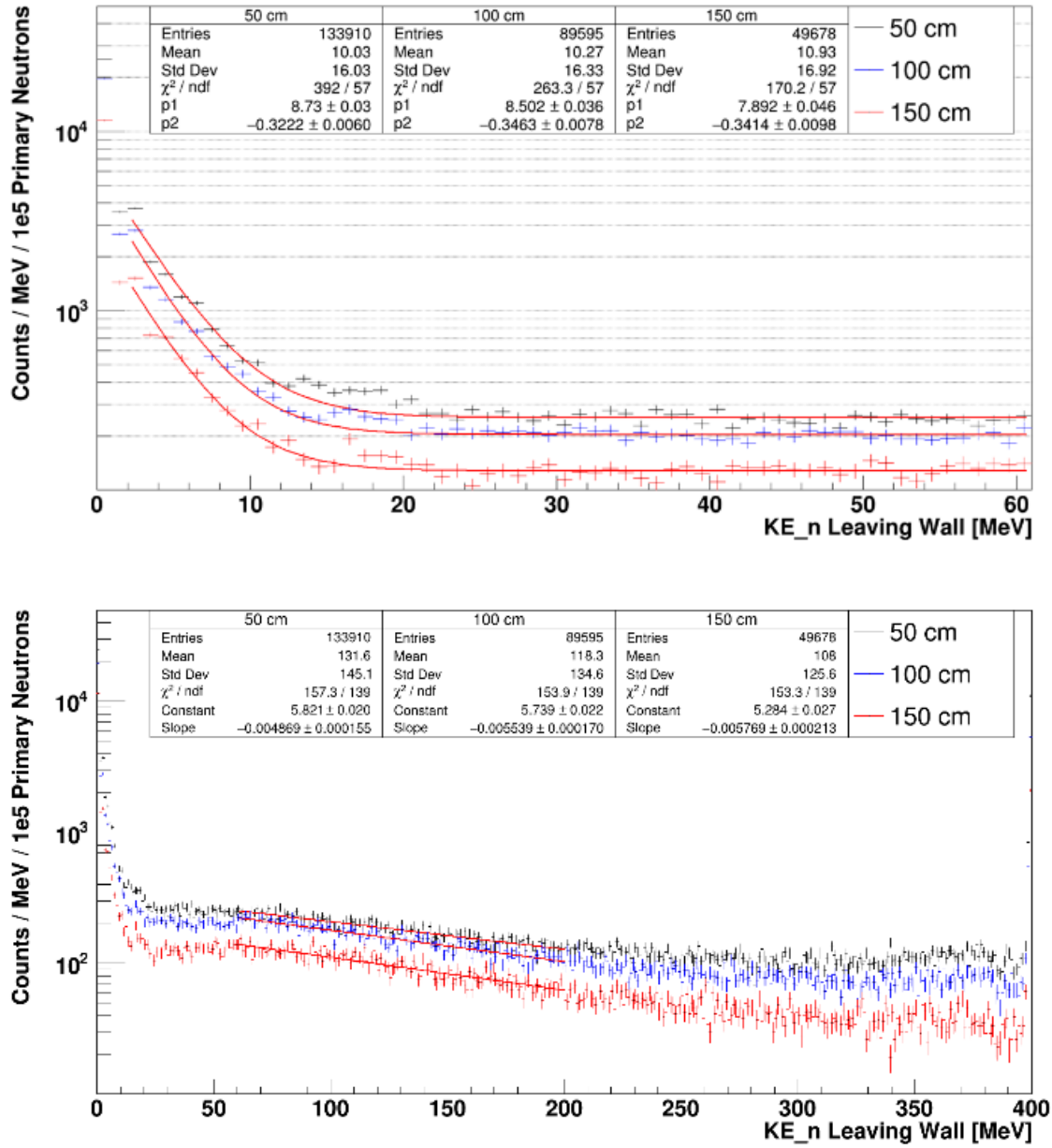


Figure 58. Neutron energy spectrum leaving concrete (Geant4 definition) wall for varying initial depth in concrete. (Top) “Low” (0-60 MeV) portion of energy spectrum containing neutrons most likely to interact in the detector volume, fit with constant + exponential. (Bottom) Full spectrum up to initial energy with exponential fit from 60-200 MeV. Particularly for the low energy portion, the spectra are very similar, and the difference in intensity can be attributed to the amount of material responsible for populating the low energy region.

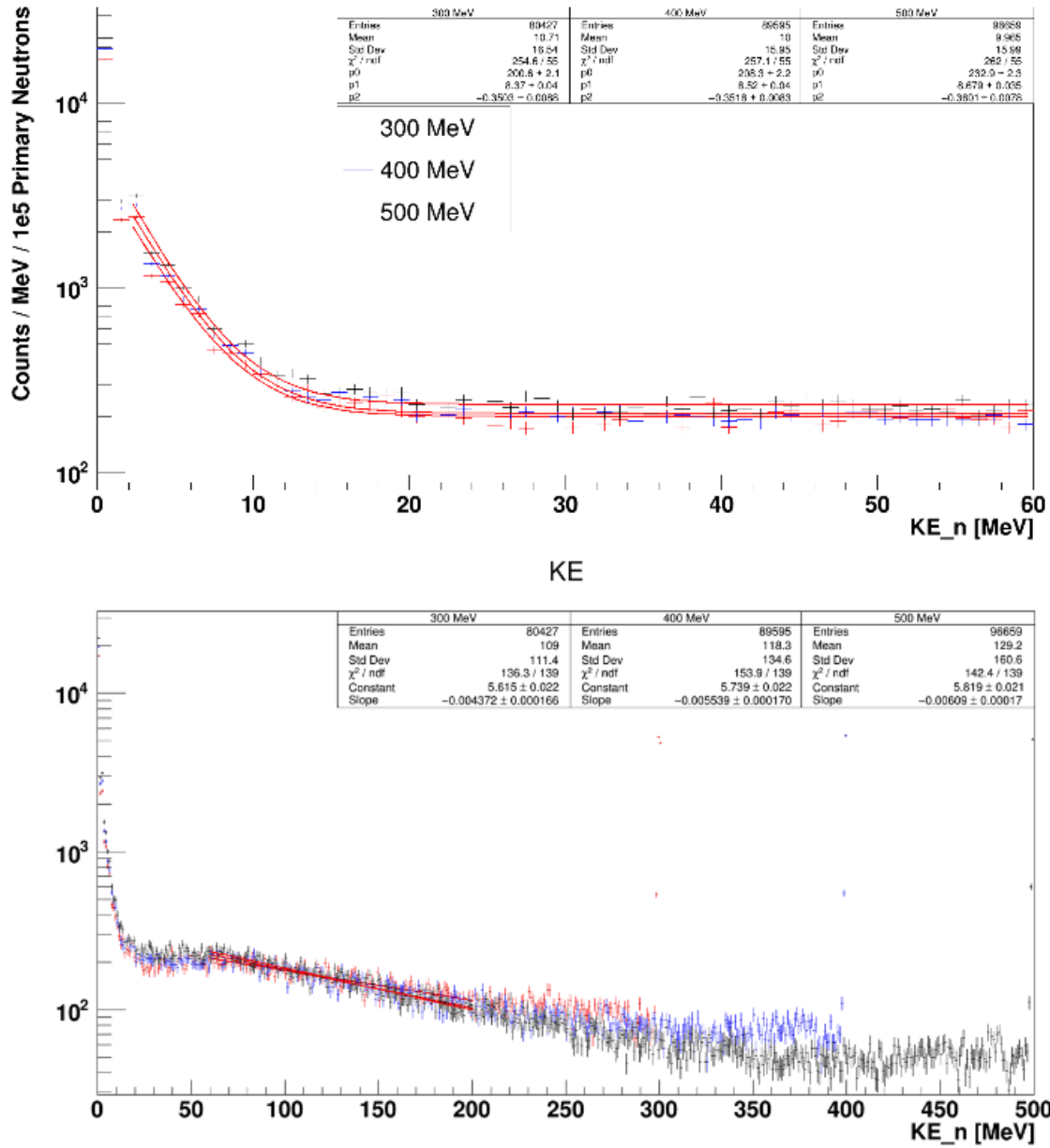


Figure 59. Neutron energy spectrum leaving concrete wall (Geant4 Definition) for varying initial neutron energy from 300-500 MeV with primary neutron beginning 1 meter deep in concrete. (Top) Low energy portion of spectra fit to constant + exponential and (Bottom) full spectrum up to initial neutron energy fit to exponential from 60-200 MeV. As with varying initial depth, particularly for the low energy portion which would be detectable, the resulting spectra have negligible difference.

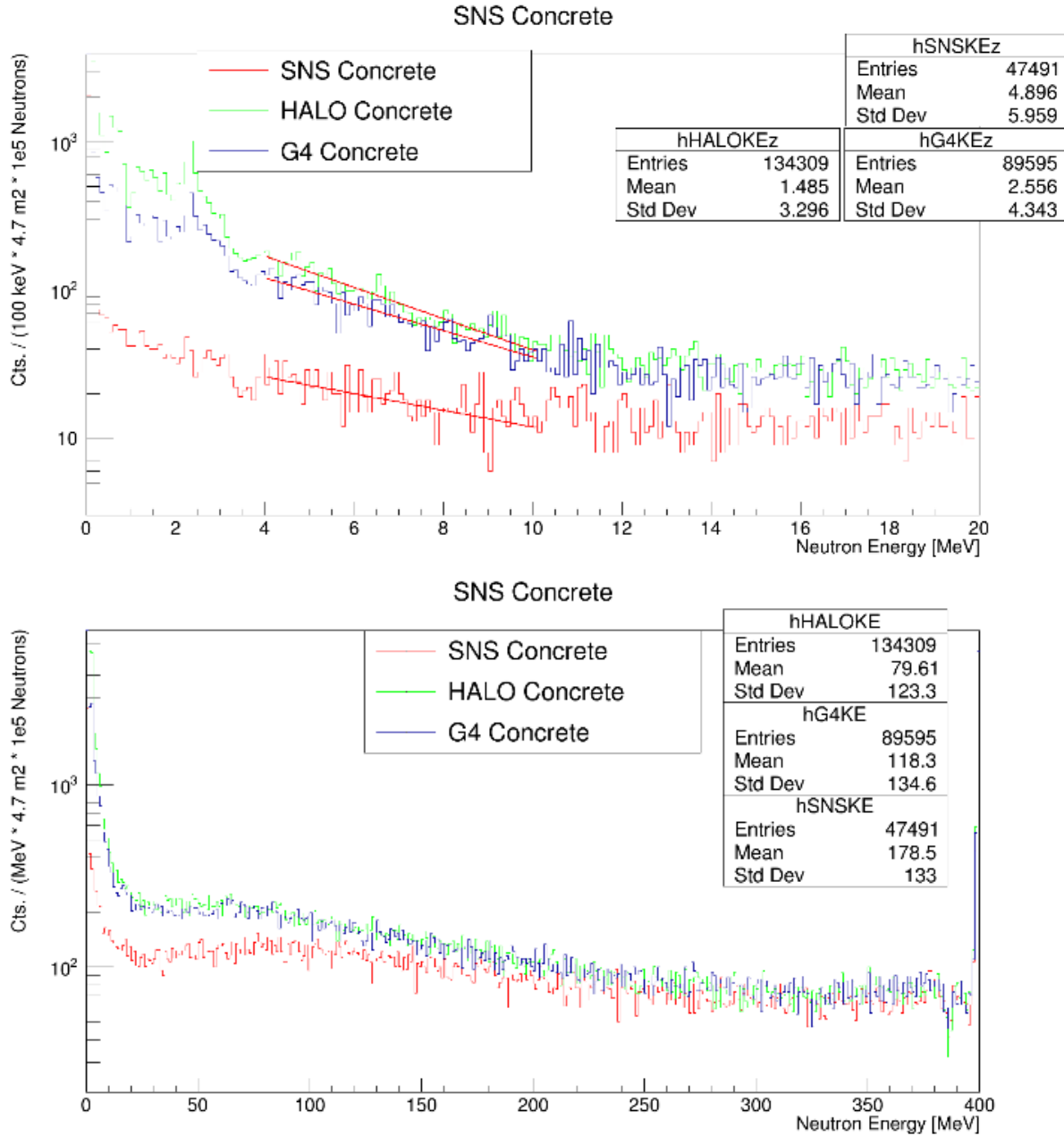


Figure 60. Neutron energy spectrum leaving the concrete wall with different concrete material definitions with 400 MeV initial energy and from 1 meter depth in concrete. The SNS concrete is slightly denser, which would have an effect similar to a different depth, but the low energy portion appears to have a different shape resulting from the slightly different composition.

### 6.5.3 High-Energy Sideband (Partial Unblinding)

Prior to unblinding of the data set, events occurring in the expected signal region between 2 microseconds prior up to 12 microseconds proceeding the SNS timing signal were excluded from the data set to avoid biasing the result. Steady-state backgrounds were still present, primarily from gamma rays. However, a major potential background still lurked within this blinded region, namely “fast” beam-related neutrons. Furthermore, the steady-state background contained very few neutrons for study of PSD parameters, as it was noted that PSD differed between calibration and SNS run data.

Beam related neutrons from other nearby locations cannot be trusted to accurately describe the BRN flux at the lead neutrino cube detector location because of the non-uniform shielding of Neutrino Alley. For example, the liquid argon detector observed different BRN rates depending on the status of the shutter from the neutron experiment hall in the target building 4 meters above, although no such correlation was observed at the location of the Neutrino Cubes. The closest location of the beam-related neutron flux was taken with the Eljen Cell measurement at the CsI location (Figure 62). The goal of unblinding a partial data set in the high energy signal region is to gain advance understanding of the BRN flux for constraint prior to full unblinding of the data where only a small fraction of NIN events would occur. Additionally, because BRNs arrive in time with the beam, we can determine the timing onset with respect to the SNS timing signal from this measurement. Steady-state backgrounds are gamma-dominated, and beam-related neutrons could provide a high purity sample of neutrons to study PSD characteristics of the liquid scintillators for this energy region.

NIN events produce low-energy nuclear recoils. The first giant dipole resonance for charged-current neutrino-nucleus scattering on  $^{208}\text{Pb}$  is  $\sim 700$  keV above the neutron separation energy leading to a peak in the emitted neutron spectrum at this energy. In the case of two neutrons, the remaining energy above two-neutron separation threshold is shared between the two neutrons. Existing predictions as well as calculations from MARLEY indicate very few neutrons produced above 5 MeV in NIN events where, by comparison, the beam related neutron spectrum extends to slightly higher energy (Figure 61). We chose a high-energy threshold of 1.5 MeV where our model predictions estimate we would only roughly 1% of our NIN signal.

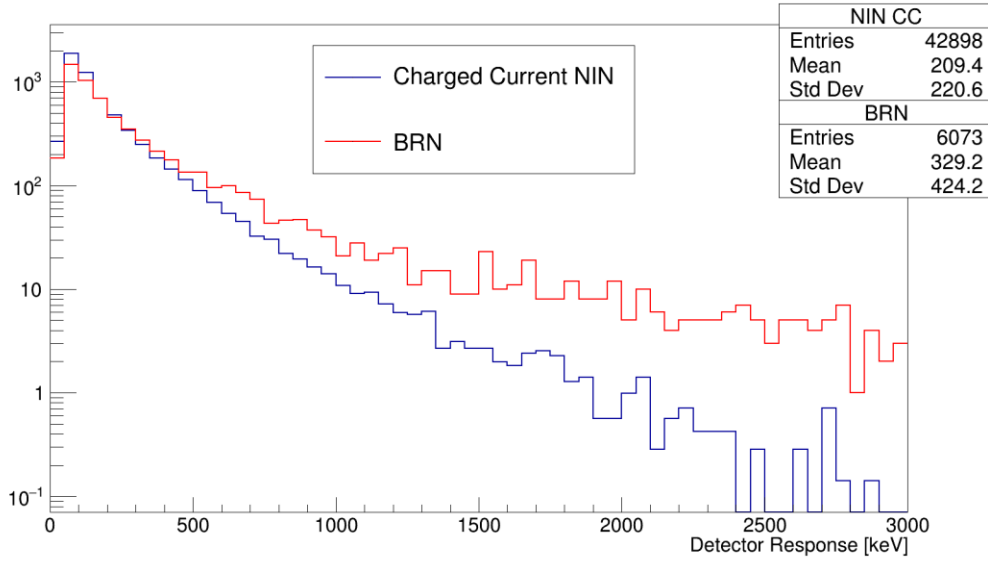


Figure 61. Comparison of simulated Beam Related Neutron (Red) and Neutrino-Induced Neutrons from charged-current (Blue) in GEANT4. The rate of BRNs to NINs is unknown, so histograms are scaled to equal number of events for shown energy range. High-Energy threshold is chosen such that less than 1% of expected NIN events are present in this selection and BRNs are expected to dominate.

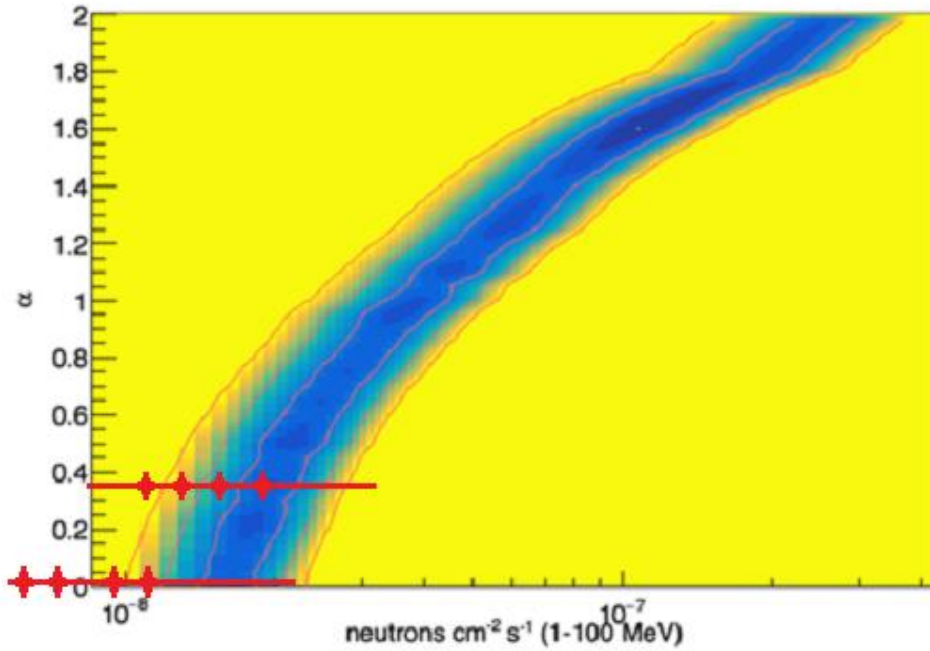


Figure 62. “Fast” beam related neutron spectrum measured by the Eljen Cell at the location of the CsI detector prior to deployment of the CsI, where the blue band is most probable set of slope/flux parameters. The vertical axis is the slope parameter of the spectrum, and the horizontal axis is the flux. Superimposed red data points are from the “High-Energy” partial unblinding of the Lead Neutrino Cube.

The gamma-dominated steady state background is also greatly reduced, allowing clean selection of BRNs, provided that the BRN rate exceeds the NIN event rate. Although other measurements are unreliable for clear predictions of BRN flux, this seemed a safe assumption based upon nearby detectors. After partial unblinding, there was only a handful of events with which to study and although it did not prove as insightful for a determinative understanding of BRNs as hoped, the uncertainty in the BRN flux at the lead neutrino cube detector location was reduced. The events were fit to the GEANT4 BRN predictions and from this the flux was determined to have reasonable agreement to a prior measurement of the BRN rate at the adjacent CsI location done with Eljen Liquid Scintillator detectors in the shielding apparatus of the eventual CsI detector without the innermost layer of high-density polyethylene neutron shielding. The data points from the high-energy unblinding of Lead Neutrino Cube data are shown superimposed over the Eljen Cell measurement in Figure 62. The slope parameter, ' $\alpha$ ', is taken from exponential fits of the neutron spectrum leaving the wall and the flux for the two fits is calculated by the number of simulated neutrons for the respective fit ranges.

#### 6.5.4 Neutron Timing Cart Measurement

In contemplation of the unexpectedly small number of BRN events in the high-energy sideband, one possible explanation was that there are simply too many attenuation lengths between the target and the detector for BRNs to take a direct path. In a complimentary effort to better understand the nature of beam related neutrons in Neutrino Alley, a recent measurement was conducted using a mobile set of liquid scintillator cells at multiple locations along the hall referred to as the Neutron Timing Cart (Figure 63) measurement which further motivated this hypothesis. At a location near the lead neutrino cube in the former footprint of the CsI detector, the BRN rate was as measured as 0.12 / hr. However, approximately 4 meters down the hall it was measured as 4.95 / hr at a location known as the Radiation Monitor (Figure 54). The wall behind this location has a gap in the shielding, noting the top-down schematic of the target and neutrino alley where there may be fewer attenuation lengths allowing fast neutrons through. This weak spot in the shielding could be the location where BRNs can enter the hallway. If so, then it should be seen that at locations further from this point would observe some delay and spread in time for neutrons with respect to the beam onset and width and indeed this was the case (Figure 64). Simulating this geometry (results in Figure 65), beginning with similar condition of



*Figure 63. Picture of Neutron Timing Cart at the Timing Rack location.*

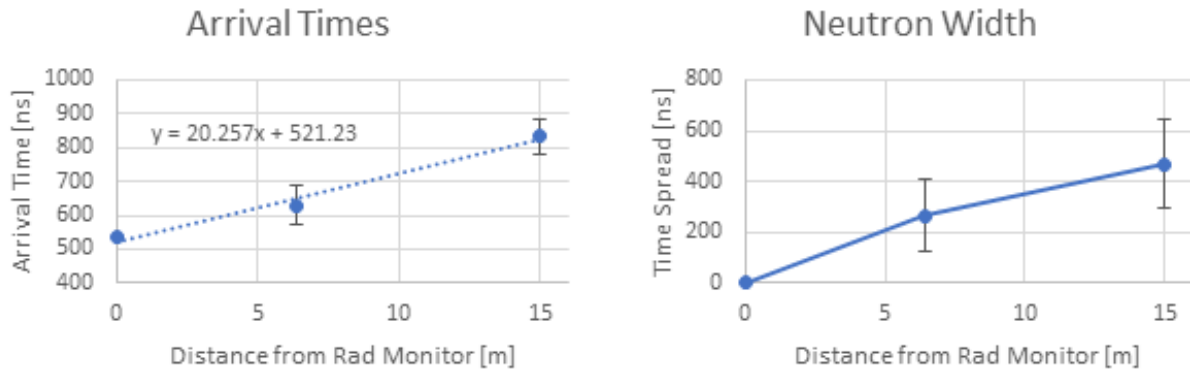


Figure 64. (Left) Neutron arrival times and (Right) spread in arrival times measured by the Neutron Timing Cart. The data points, from left to right in each image are from the Radiation Monitor, CsI detector footprint, and Timing Rack respectively.

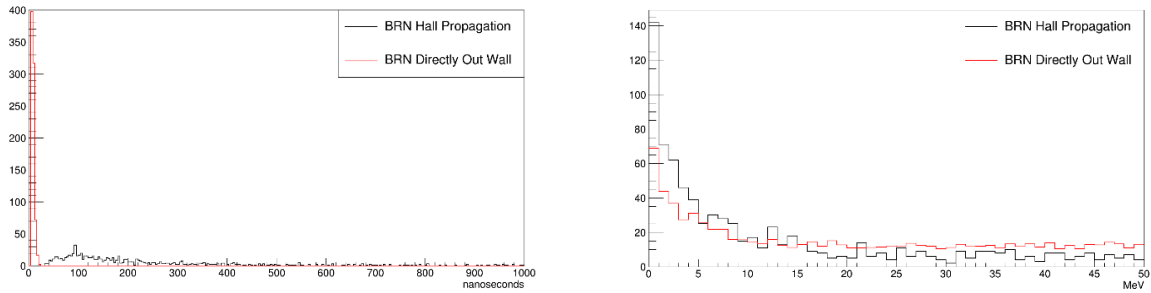


Figure 65. Comparison of BRN Models simulated in GEANT4 – one out directly out of the wall and the other with the detector located an average distance of 4.5 meters (approximately distance of Lead Neutrino Cube to Radiation Monitor). For the hallway propagation, the time (left) and energy (right) is taken for neutrons reaching the exterior of the detector shielding. For directly out wall, these values are for when the neutron exits the concrete. The time distribution (left) supports the conclusions of the Timing Cart Measurement and consequently the energy spectra (right) as evidenced by the spread in arrival times.

monoenergetic neutrons one meter deep inside the concrete then out of the wall, and then counting those which scattered  $90^\circ$  to propagate along Neutrino Alley and reach the Neutrino Cube yielded small statistics for large computation time and was not implemented in the final analysis but done as confirmation of the Neutron Timing Cart's measurement. These conclusions came near the time of the full-unblinding and analysis, and with the BRN characteristics being so uncertain, timing onset, time spread, and flux normalization were given large ranges to float in the BRN PDF.

## 6.6 Signal PDF Design

For both NINs and BRNs, simulations were done with all three detector configurations: 4 cylinders, 2 cylinders and two vacant cavities, and then 2 cylinders and 2 hexagonal liquid scintillators. The event generator for both these signals is described in previous sections, and the outputs are in identical format such that the same post-processing scripts can be used to convolve the simulation output with quenching data, detector energy scaling and resolution as well as thresholds. Quenching is applied based on reference [88] and for proton recoils below 100 keVnr, quenching information from reference [89] is used. Similar to how data is processed, only the first 400 ns after the initial recoil is integrated into simulated events and subsequent interactions are ignored, mimicking the hold-off time used in data processing. Simulation of pulse shape discrimination was investigated but would require full waveform simulation and this task proved unreliable at reproducing accurate PSD values. As a proxy for pulse shape discrimination between nuclear and electron recoils, the event information is considered in post-simulation processing and nuclear recoils were required to have less than 5% contamination of total interaction energy, after quenching. Studies of this from simulation determined only a small overall impact on detector signal, as neutron events primarily produce nuclear recoils. Following this treatment, the results from GEANT4 and MCNP simulations were in identical format and differed by less than 3%.

For neutrino flux predictions, a weighted average distance of 18.88 m from the SNS target is used. For each run, the beam energy and beam power of the SNS were queried from an Experimental Physics and Industrial Control System (EPICS) database and the number of neutrinos generated from each run were determined from these parameters and the energy

dependent fits in reference [90]. The neutrino-induced neutron signal prediction is scaled by this information. A flow chart of this process is illustrated in Figure 66. Estimates of the prompt beam-related neutron background are based upon fits of model predictions to nearby measurements and are also scaled by EPICS database run information.

The timing structure of the neutrino signal is determined by the average proton-on-target (POT) trace of the golden run data periods of each detector. The POT trace is then convolved with a 26 ns exponential decay corresponding to the lifetime of the pion. The resulting distribution is then again convolved with the 2197 ns exponential decay for the subsequent muon decay. This is then convolved with the simulated detector response time and a 0.9 ns Gaussian to incorporate the single electron jitter in the E9821B phototube [91]. The process for NIN model signal predictions is illustrated in Figure 67.

Beam-related neutron timing distribution follows the average POT trace as well convolved with timing from detector simulation and PMT response as with the NIN timing structure. As discussed in section 6.5.4, the Neutron Timing Cart measurement observed some time dispersion of beam related neutrons arriving in Neutrino Alley and as a result the width of this broadening is allowed to float. The onset time for both BRN and NIN timing PDFs with respect to the SNS timing signal Event 39 is allowed to float as well. The resulting PDFs of NIN, BRN, and steady-state background (informed by unblinded data) are shown in Figure 68.

## 6.7 Final Fitting Criteria and Results

A one-dimensional timing-only approach was chosen for fitting the signal. Considering the model dependence of neutrino-induced neutron spectra, particularly regarding the lack of contribution of forbidden transitions in current signal predictions, energy is not chosen as a fit parameter. Instead, an energy cut was chosen to optimize the expected signal in conjunction with arrival time to optimize signal to background. The optimal time-energy region for each detector can be found in Table 12. The low energy bound is set by the PSD threshold for each detector.

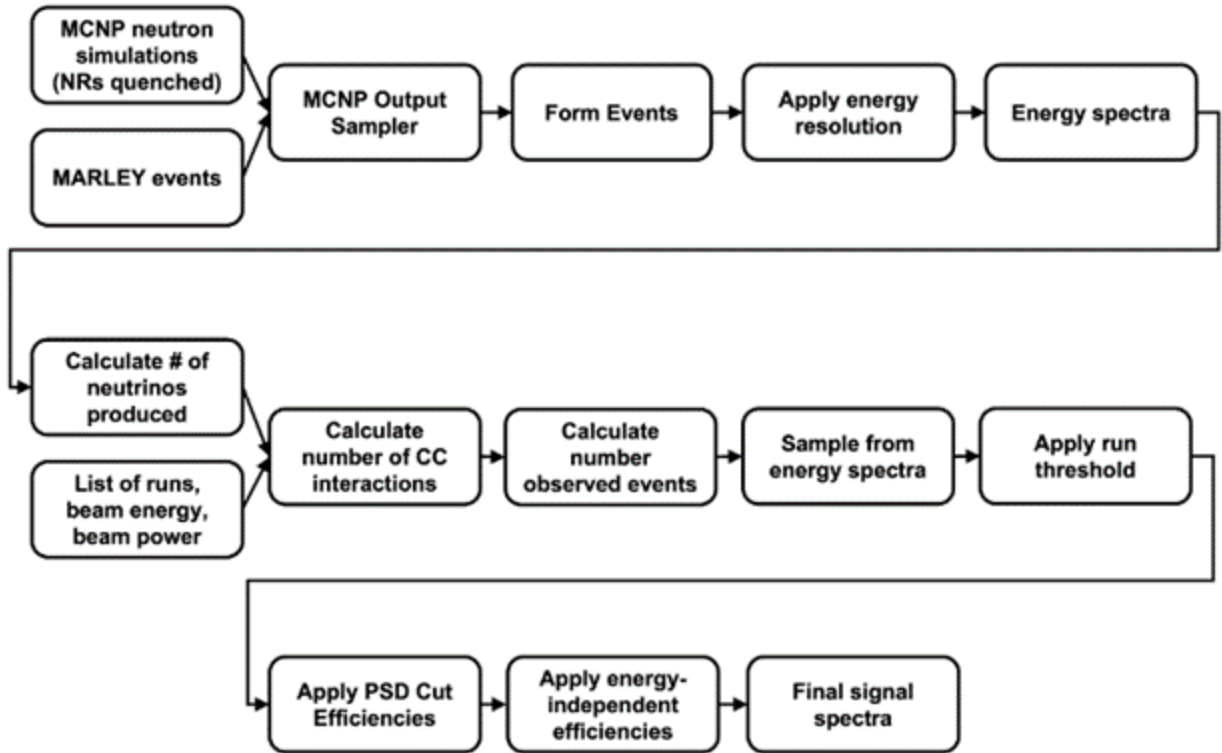


Figure 66. Overview of the steps for producing  $^{208}\text{Pb}$  charged-current energy predictions in MCNP. GEANT4 simulations are processed nearly identically with the exception that GEANT4 can use MARLEY model predictions as simulation input [70].

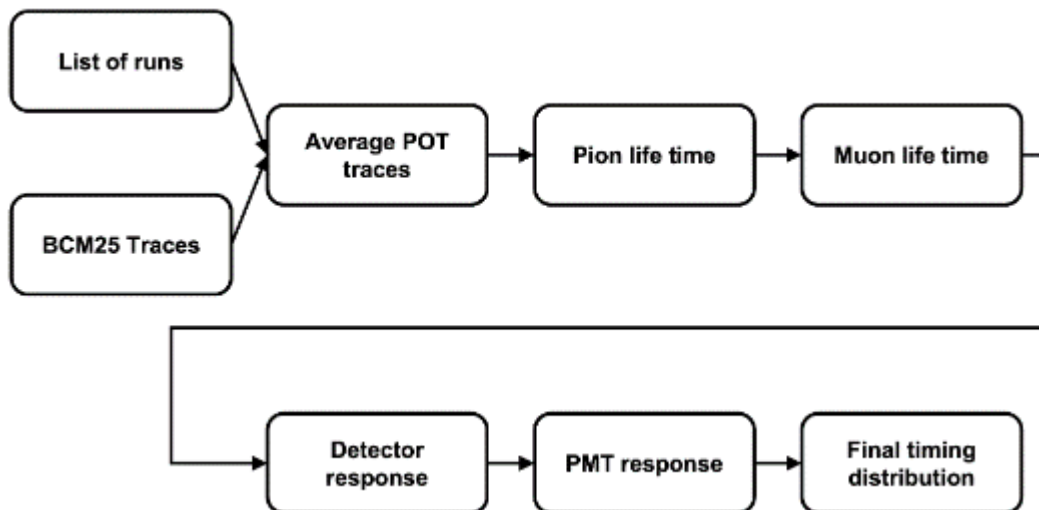


Figure 67. Overview of steps for producing  $^{208}\text{Pb}$  charged-current timing predictions [70].

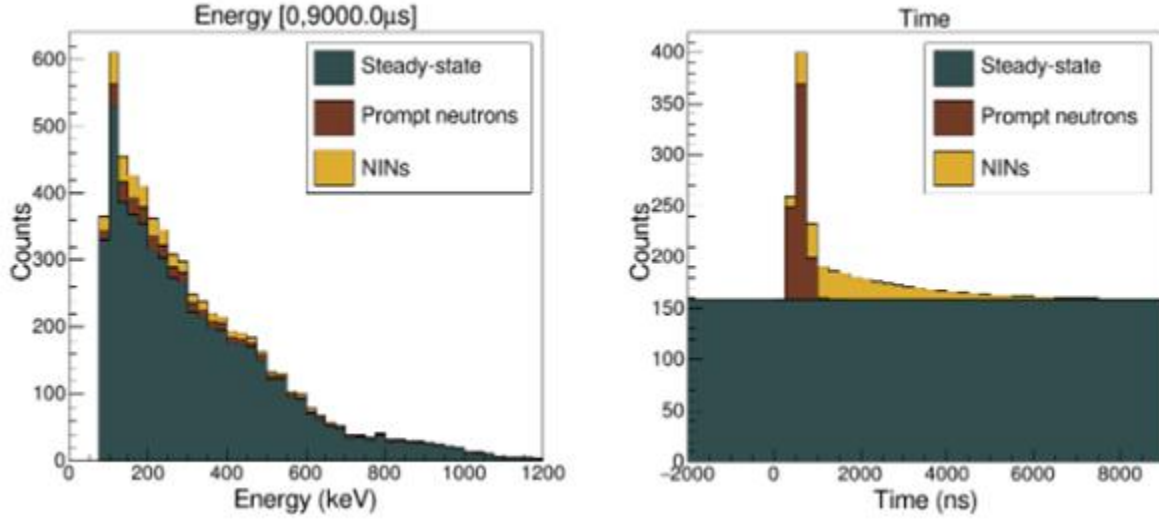


Figure 68. 1D energy and timing PDFs for NINs, prompt neutrons, and steady state backgrounds, after applying PSD cut. The energy distribution is for a time interval of 0-9μs after event 39, and the energy distribution is from the lower PSD threshold to 1200 keV [70].

Table 12. Optimized signal region of interest in energy and time for each channel and its individual expected sensitivity [70].

| Channel | Energy Window [MeV] | Time Window [ns] | Sensitivity [ $\sigma$ ] |
|---------|---------------------|------------------|--------------------------|
| 0       | [90,535]            | [550,4200]       | 1.16                     |
| 1       | [90,735]            | [680,4230]       | 3.57                     |
| 2       | [90,770]            | [760,4190]       | 3.15                     |
| 3       | [170,825]           | [480,4090]       | 0.81                     |
| 12      | [170,495]           | [760,4620]       | 1.79                     |
| 13      | [95,425]            | [710,4400]       | 2.81                     |

Below is the list of parameters and their tolerance ranges used as input for fitting in the final unblinding procedure:

- **Steady-State Background Rate:** the background of steady state components was able to float to half from its predicted value up to twice its value.
- **Prompt Neutron Rate:** The amplitude of the prompt background components was allowed to float from 0.1x the expected amplitude to 10x the expected amplitude allowing for large uncertainty in prompt neutron flux.
- **Prompt Neutron Timing Offset:** BRN arrival time is known with sub-100 ns accuracy. Still time of prompt neutrons relative to event 39 allowed to float within 1 microsecond of nominal position.
- **Prompt Neutron Smearing:** As prompt neutron backgrounds propagate to the detector, there may be additional spreading due to the difference in energy of the neutrons. An additional Gaussian smearing term is added to the prompt neutron time distribution with a sigma floating between 0 to 250 ns.
- **Neutrino-Induced Neutron Rate:** the amplitude of neutrino-induced neutrons was allowed to float to zero and up to 3x number of expected events.
- **Neutrino-Induced Neutron Timing:** The timing of neutrino induced neutrons was calculated based on time-of-flight, detector response, and cable delays. The width is set by the uncertainty of the timing measurements.

Toy data sets with varying input parameters of simulated PDFs were generated using Duke MCNP and my GEANT4 Monte Carlo simulations to test the fitter's ability to reproduce input parameters and test for bias. 500 toy data sets were generated to test the expected sensitivity, resulting in an expected mean sensitivity of  $5.61\sigma$  (Figure 69). After determining optimal parameter ranges and testing procedures on toy Monte Carlo data sets, we unblinded detector data and proceeded to fit selected "Golden Run" data. The cumulative error on the expected signal for NINs is listed in Table 13.

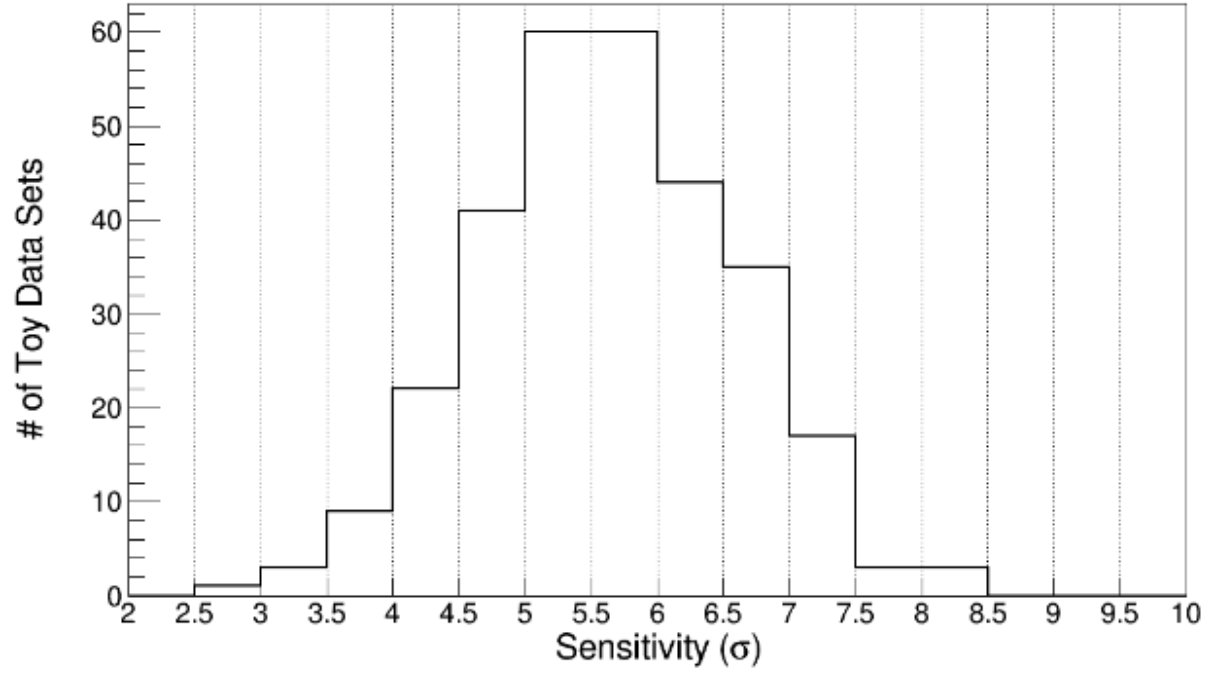


Figure 69. Sensitivity distribution for 500 toy data sets generated with Poisson statistics [70].

Table 13. Error budget for final fit and run criteria [70].

| Quantity           | NIN Uncertainty [%] |
|--------------------|---------------------|
| Neutrino flux      | $\pm 10$            |
| Quenching Factor   | $\pm 2.7$           |
| Software threshold | +0.2 -0.4           |
| PSD cut            | $\pm 1.0$           |
| Calibration        | +2.1 -2.2           |
| Energy Resolution  | +1.7 -0.5           |
| Muon Veto          | +0.4 -0.3           |
| Lead target mass   | $\pm 0.6$           |
| <b>Total:</b>      | <b>+10.8 -10.7</b>  |

The final fit of signal and background PDFs to data, with tolerance ranges listed above in the previous section and time-energy region of interests from Table 12, is shown in Figure 70 using two different fitters, iminuit [92] and LDMAAna (used in CsI analysis [50]). The surprising result is consistent with 0 NINs and places a limit on the cross-section for this process at 20% of its theoretically predicted value. The fit results are listed in Table 14. All fit parameters are close to expected values with the exception of NINs.

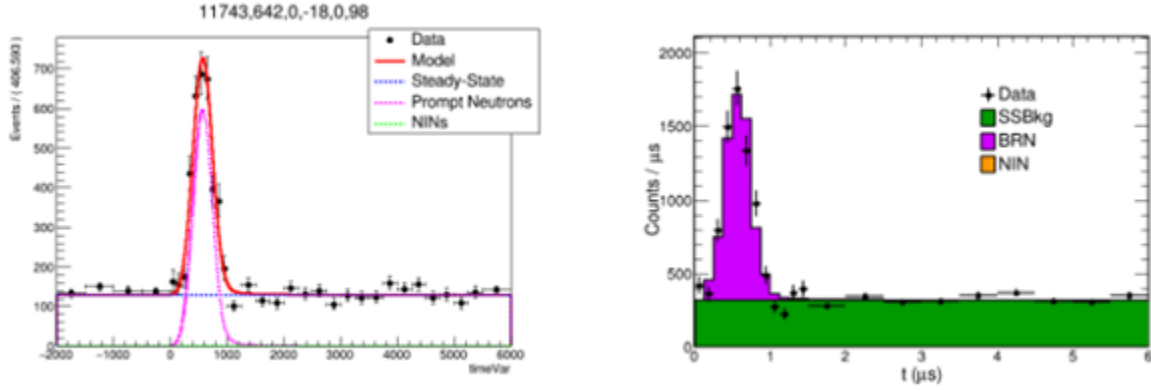


Figure 70. (Left) Plot of PDFs with best-fit iminuit and (right) Plot of PDFs with best-fit LDMAna results [70].

Table 14. Fit results from iminuit, emcee, and LDMAna. A profile based on the emcee results yields a NIN amplitude consistent with zero [70].

| Parameter                 | Expected            | iminuit                      | emcee                        | LDMAna   |
|---------------------------|---------------------|------------------------------|------------------------------|----------|
| Steady-State Amp.         | 11,664              | $11,555.3^{+122.4}_{-111.3}$ | $11,553.7^{+110.7}_{-110.5}$ | 11,672.4 |
| Prompt Amp.               | $572^{+116}_{-116}$ | $638.6^{+34.8}_{-31.6}$      | $632.1^{+31.0}_{-31.6}$      | 640.4    |
| NIN Amp.                  | 309                 | $0^{+42}$                    | $31.67^{+35.6}_{-22.4}$      | 0        |
| Prompt Time Shift (ns)    | 0                   | $-18.7^{+16.7}_{-16.7}$      | $-20.7^{+9.5}_{-9.2}$        | 11.9     |
| NIN Time Shift (ns)       | $0^{+37.8}_{-37.8}$ | $0^{+37.8}_{-44.1}$          | $-1.01^{+37.2}_{-36.9}$      | 0        |
| Add. Prompt Smearing (ns) | -                   | $98.7^{+15.7}_{-14.2}$       | $97.0^{+14.4}_{-15.2}$       | 91.1     |

# Chapter 7

## Results and Conclusions

While no result is still a result, it does merit some extra thought. We accept our results. This places an upper limit on the  $^{208}\text{Pb}$  NIN cross section of  $1/5^{\text{th}}$  its theoretical value. As far as questioning our data and processing, we know some things for sure: 1) Neutrinos are being produced and  $\text{CE}\nu\text{NS}$  measurements at other detectors are consistent with flux predictions and 2) The Pb Neutrino Cube can see neutrons based on the  $^{252}\text{Cf}$  calibration runs and presence of prompt, beam related neutrons. After multiple reviews, we are confident in the fidelity of our data set. In the COHERENT collaboration, two groups, University of Tennessee and Duke University had mostly independent run data analysis coming to the same conclusion. As we move forward, one avenue of improvement would be more detailed BRN studies to produce a model that accounts for their increased spread and delay in time, however it cannot increase the NINs production cross-section. Another would be to modify theoretical models to include forbidden transitions in MARLEY. Although neither of these options would explain the lack of NINs present in the data set. One possibility is  $g_A$  quenching, which is not correctly included in the theoretical models for neutrino interactions. Recently such possibility became of interest again after new results from the BEST (Baksan Experiment on Sterile Transitions) [93]. Here a deficit in the rate of neutrino interaction in gallium detectors from an artificial neutrino source has an interpretation supporting the existence of sterile neutrinos (similar to gallium anomaly for solar neutrinos). However, an easier explanation could be that  $g_A$  quenching in the interaction cross-section on gallium is not calculated correctly.

Of course, it would be most satisfying to definitively confirm the suppression inelastic neutrino-nucleus interactions with multiple detectors and possibly other targets, potentially with the capacity to see the leptonic component of charged-current interaction. Nevertheless, this unexpected new result should merit some interesting considerations from nuclear theory.

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# Vita

Brandon Becker was born in Sacramento, CA on February 15, 1991. He attended Ponderosa High School in El Dorado County, California and graduated in 2009. He then attended California Polytechnic State University, San Luis Obispo for a B.S. in Physics until 2013 and was accepted into the Ph.D. program of the Department of Physics and Astronomy at the University of Tennessee, Knoxville in the Fall of 2014.

During his studies at the University of Tennessee he had the opportunity to gain experience with programming in C++ and Unix based environments, perform hands-on work for research and development of detectors and electronics through access to the Oak Ridge National Laboratory and other facilities aligned with collaboration research objectives, develop software for the simulation and analysis of detectors with Geant4 and CERN ROOT, and present ongoing research and results at public conferences.

Brandon has presented at APS Division of Particles and Fields 2017, APS April Meeting 2018 Columbus, and APS April Meeting 2019 Denver. His work has contributed to COHERENT Collaboration publications such as

Observation of Coherent Elastic Neutrino Nucleus Scattering.

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First constraint on coherent elastic neutrino-nucleus scattering in argon. *Phys. Rev. D* 100, 115020 – Published 9 December 2019.

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Development of a  $^{83m}\text{Kr}$  source for the calibration of the CENNS-10 liquid argon detector. COHERENT collaboration et al 2021 JINST 16 P04002.

A D<sub>2</sub>O detector for flux normalization of a pion decay-at-rest neutrino source.  
COHERENT collaboration *et al* 2021 *JINST* **16** P08048.

Simulating the neutrino flux from the Spallation Neutron Source for the COHERENT experiment. arXiv:2109.11049 [hep-ex].

He is grateful for this opportunity and intends to pursue future opportunities where his experience as a student at University of Tennessee can serve well.