

Measurement of Theta-13 Neutrino Mixing Angle from the Disappearance of Electron Antineutrinos at the Double Chooz Experiment

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Abstract

The measurement of the remaining neutrino-mixing angle, θ_{13} , is a critical step toward further understanding of neutrino properties and to guide future neutrino oscillation experiments. Double Chooz has a unique opportunity to perform this measurement building on the original CHOOZ reactor anti-neutrino experiment, the experience that set the previous limits on θ_{13} . In the first phase of Double Chooz, 101 days of data was analyzed with only the far detector operating of a two-detector plan. In this thesis I will describe the design of the low background neutrino detector and the oscillation analysis performed. From the deficiency between the expected and measured number of electron anti-neutrinos a value of $\sin^2(2\theta_{13}) = 0.104 \pm 0.03(\text{stat}) \pm 0.076(\text{syst})$ was found for rate only analysis and $0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$ with the rate and spectral energy shape analysis.

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Chapter 1

Introduction

The neutrino has been an elusive particle that historically dates back to the early research into nuclear beta decay up to the late 1920s. In early experiments researchers found the instead of a discrete energy of electrons originating in beta decays the spectrum was continuous. To explain the electron energy spectrum, Wolfgang Pauli proposed a new particle in his famous letter to the participants of a physics conference in Tübingen, Germany. Pauli's proposed "desperate remedy" was neutral, spin $\frac{1}{2}$ particles whose mass is on the order of or smaller than the electron, which he called "neutrons". The neutral energy carrier would allow for conservation laws to be preserved. His postulation came with an apology due to the difficulty in detecting such a particle. "I have done a terrible thing, I have postulated a particle that cannot be detected" [1]. After the discovery of the heavy neutron, Enrico Fermi dubbed Pauli's particle neutrino in 1933. Fermi attempted to theorize beta decay with the inclusion of the neutrino as neutron transition into a proton, electron and neutrino; $n \rightarrow p + e^- + \nu$. In his theory the neutrino is either massless or of very small mass compared to the electron. This conclusion was based on the experimental shape of the electron spectrum [2] (figure 1.1).

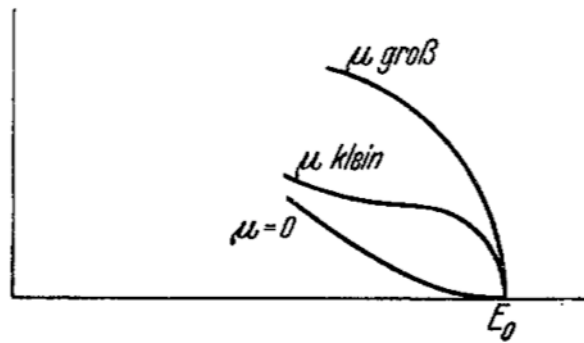


Figure 1.1: The end of the electron energy spectrum in beta decay for various magnitudes of the neutrino mass (μ). klein – small, groß – large. [3]

It would take over twenty years until Reines and Cowan detected the electron anti-neutrino in 1956. The muon neutrino was detected in 1962 at Brookhaven national lab [4]. Pontecorvo first proposed neutrino oscillations in 1957, who first thought that the neutrino would oscillate into an anti-neutrino. The postulate of oscillations was revised to neutrino flavor oscillation (ν_e to ν_μ) by Maki, Nakagawa and Sakata in 1962 [5]. Solar neutrino deficits measured at the Homestake experiment (chapter 3.2) in 1968 gave the experimental basis for the possibility of neutrino flavor change. Neutrino oscillations have been a major experimental focal point over the past decades. The existences of neutrino oscillations require a massive neutrino and in which neutrino flavor eigenstates are different from neutrino mass eigenstates. There are three angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and two mass splitting terms that parameterize oscillations (Chapter 2.2). Previous to the Double Chooz experiment only one of these parameters remains unmeasured, θ_{13} . In the following chapters more details will be given on current neutrino physics and oscillation (Chapter 2) and neutrino experimental history (Chapter 3).

Reactor neutrino experiments have played an important role in the study of neutrinos beginning with the first detected neutrinos (Chapter 3.1). There have been six short-baseline reactor neutrino experiments of note; Bugey, Gosgen, Krasnoyarsk, ILL, Rovno and Savannah River (Chapter 3.5). Each of these was at a baseline below 100-meters and yielded no evidence of oscillations. The KamLAND experiment provided compelling evidence to the oscillatory nature of neutrinos. Electron anti-neutrinos coming from the 55 nuclear reactors of Japan were detected in KamLAND at an average base line of 180km [6]. With over five years of running KamLAND was able to precisely measure oscillation parameters θ_{12} and Δm^2_{21} (Chapter 3.4).

For a base-line sensitive to the θ_{13} parameter, the CHOOZ experiment (Chapter 3.5.2) was located ~ 1 km from two reactors in Northeast France and Palo Verde (Chapter 3.5.3) was located .89 km and .75 from three reactors in Arizona. CHOOZ was only able to set an upper limit on $\sin^2(\theta_{13}) < 0.15$ [7]. The experience from the original CHOOZ experiment was expanded on with the Double Chooz experiment. In Chapter 4 and Chapter 5 of this thesis a detailed description of the Double Chooz experiment and

expected signals are provided. The analysis for the first 101 days of data taking for Double Chooz suggests a non-zero value of θ_{13} . In Chapter 6 the detector response is described followed by the analysis of this four-month data in Chapter 7. Included in the analysis are candidate extraction, background determination, and neutrino oscillation calculations.

Chapter 2

Neutrino Physics

Chapter 2.1

Standard Model

The Standard Model (SM) is the theoretic foundation of elementary particles and their interactions. The Standard Model consists of twelve fundamental particles (and corresponding twelve anti-particles) and four force carriers (photons, gluons, W and Z bosons). Of the twelve fundamental particles there are six quarks (three up-type and three down-type), three charged leptons and three neutral leptons. The particles are grouped into three generations with each generation containing two quarks and two leptons (Figure 2.1).

The Standard Model of electroweak theory describes the combination of electromagnetic and weak currents. There are four force carriers of the electroweak interactions. Photons mediate electromagnetic interactions are only applied to charged fermions. For the weak force there are three force carriers, W^- , W^+ and Z bosons. Neutrinos, which have no electric charge, only interact via the weak force. Interactions in which there is emission or absorption of a W^- or W^+ are called charge current. Charge current interactions with a neutrino flavor will also involve the matching charged lepton. Neutral current interactions involve the exchange of a Z boson (figure 2.2).

Generation	I	II	III
<i>quarks</i>	u	c	t
	d	s	b
<i>leptons</i>	ν_e	ν_μ	ν_τ
	e	μ	τ

Figure 2.1: Standard Model Particles

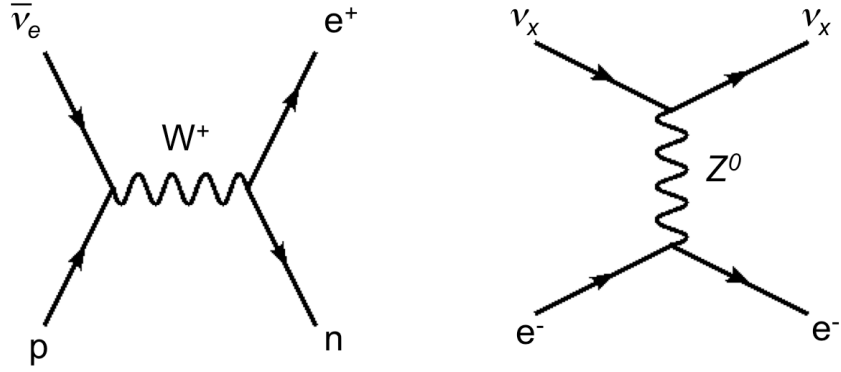


Figure 2.2: Example of charged current interaction (left) and neutral current interaction (right).
 x – is any of the three lepton flavors

Within the framework of the standard model there are three neutrino generations, ν_e , ν_μ , ν_τ , which are paired with the three types of charged leptons. There has been experimental verification for the existence of each flavor. There is also indirect evidence for the existence of only three light neutrino flavors from the decay of the Z-boson. The measured hadronic cross-section at the Z resonance (figure 2.3) is observed from e^+e^- collisions at LEP. The hadronic cross-section (equation 2.1) is dependent on the total and partial decay widths (equation 2.2).

$$\sigma_{had} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee} \Gamma_{had}}{\Gamma_Z^2} \quad (2.1)$$

$$R_{inv/l} = \frac{\Gamma_{inv}}{\Gamma_{ll}} = N_\nu \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{ll}} \right)_{SM} \quad (2.2)$$

where m_Z is the Z boson mass, l is any charged lepton, Γ_{inv} is the invisible partial decay width, and N_ν is the number of light neutrinos. The best fit to flavors of neutrinos 2.9840 ± 0.0082 [8].

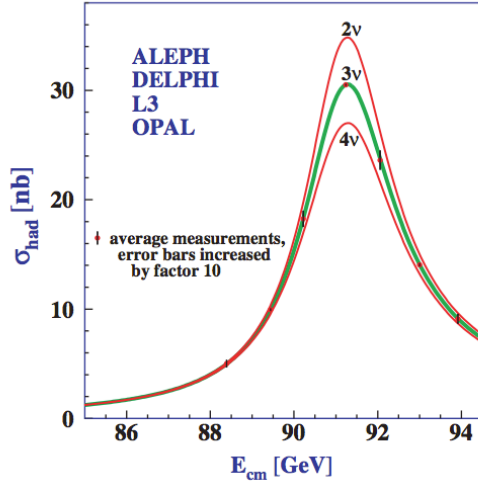


Figure 2.3: The measured hadronic production cross-section versus center of mass energy around the Z mass for e^+e^- collisions. The dependence on the number of light neutrino generations is shown [8].

There are some hints to the existence of additional sterile neutrino flavors. Sterile neutrinos are those that do not undergo weak interactions and require physics beyond the standard model. The LSND experiment reported an excess of electron anti-neutrinos arising from oscillations of muon anti-neutrinos. Such excess would require the existence of additional neutrino flavor with a large mass splitting ($\sim 1\text{eV}$) [9]. Recent theoretic revaluations of the reactor neutrino flux also hinted at additional neutrino flavors. Called the “Reactor Antineutrino Anomaly”, in which the total calculated flux of antineutrinos from nuclear reactors was increased by 3%. This increased flux meant that the ratio of observed to predicted antineutrino rates for all short baseline experiments ($<100\text{m}$) is 0.943 ± 0.023 [10]. This would indicate that a fourth neutrino flavor was present which impacts oscillations at short distances. For this thesis only a three-flavor neutrino model is implied but the impact on θ_{13} searches should be considered for future analysis.

Chapter 2.2:

Neutrino Oscillations

2.2.1 Three Flavor Vacuum Oscillations

Neutrinos are created and detected in their flavor states via weak interactions. The propagation of neutrinos are dictated by their mass states. For particles such as the charged leptons, the flavor states have a distinct mass. Neutrinos however have three mass eigenstates, ν_1, ν_2, ν_3 , do not match directly with the flavor eigenstates. Instead the flavor states are superposition of the mass states:

$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}^* |\nu_j\rangle \quad (2.3)$$

ν_α are the flavor eigenstates (e, μ , τ) and ν_j are the mass eigenstates (1, 2, 3). The matrix $U_{\alpha j}$, named after Pontecorvo-Maki-Nakagawa-Sakata (PMNS), describes the mixing amplitude between the flavor and mass eigenstates. The matrix:

$$U_{\alpha j} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \quad (2.4)$$

is a 3x3 complex matrix for the three flavor neutrino theory. A complex matrix will contain $n \times n$ complex parameters and $n \times n$ real parameters for a total of $2n^2$ parameters (18 parameters for a 3x3 matrix). Constraints using unitary conditions,

$$\sum_i U_{\alpha i}^* U_{\beta i} = \delta_{\alpha\beta} \quad (2.5)$$

removes 9 parameters. Re-phasing, or multiplying any column or row by a complex phase factor, can constrain 3 additional parameters. Two complex phases are present if neutrinos are Majorana particles (neutrino is its own antiparticle). These phases are not significant to oscillations and are omitted. The PMNS matrix can be expressed as three rotational angles and one complex phase:

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{12}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \quad (2.6)$$

In the matrix $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$, where θ_{ij} represents the mixing angles and δ is the complex phase CP violating phase [11].

To understand neutrino mixing the evolution of a neutrino from creation to detection must be examined. A neutrino is produced via a weak interaction and propagates through space. The neutrino is then detected via another weak interaction. The probability of oscillation from one flavor to another is expressed in terms of the amplitude of phase oscillation:

$$\text{Prob}(\nu_\alpha \rightarrow \nu_\beta) = \left| \text{Amp}(\nu_\alpha \rightarrow \nu_\beta) \right|^2 \quad (2.7)$$

The quantum mechanical amplitude has three terms including the amplitude of the weak interactions creating and detecting the neutrino (from the PMNS matrix terms) and the propagation of the neutrino.

$$\text{Amp}(\nu_\alpha \rightarrow \nu_\beta) = \sum_i U_{\alpha i}^* \text{Prop}(\nu_i) U_{\beta i} \quad (2.8)$$

The propagation amplitude term arises from the time evolution of the mass eigenstate. This propagates as a wave function giving:

$$\text{Prop}(\nu_i) = e^{-im_i\tau} \quad (2.9)$$

Where m_i is the mass of the eigenstate i , and τ is the proper time in the neutrino rest frame. The term $m_i\tau$ can be expressed in the lab frame using Lorentz invariance as $E_it - p_iL$, where L is the distance traveled in time t of the lab frame. Relativistic approximation for neutrinos gives a propagation term of a single mass state as:

$$\text{Prop}(\nu_i) = e^{-im_i^2 L / 2E} \quad (2.10)$$

From equations 2.7, 2.8 and 2.10, the probability of flavor state change becomes:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\alpha j}^* e^{-im_j^2 \frac{L}{2E}} U_{\beta j} \right|^2 \quad (2.11)$$

Squaring the terms of the unitary matrix gives:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) = & \delta_{\alpha\beta} - 4 \sum_{j>i} \text{Re} \left(U_{\alpha j}^* U_{\beta j} U_{\alpha i} U_{\beta i}^* \right) \sin^2 \left(\Delta m_{ji}^2 \frac{L}{4E} \right) \\ & + 2 \sum_{j>i} \text{Im} \left(U_{\alpha j}^* U_{\beta j} U_{\alpha i} U_{\beta i}^* \right) \sin \left(\Delta m_{ji}^2 \frac{L}{2E} \right) \end{aligned} \quad (2.12)$$

From this, the probability of oscillations depends on the terms of the PMNS matrix, the mass splitting term $\Delta m_{ji}^2 = (m_j^2 - m_i^2)$, and L/E . L is the distance the neutrino travels and

E is the neutrino energy and are values that are set experimentally set. With the condition that $\Delta m_{13}^2 + \Delta m_{21}^2 + \Delta m_{31}^2 = 0$, there are only two independent Δm^2 terms. The Δm_{ji}^2 term is important to the concept of neutrino oscillations in that it requires massive neutrinos. As an example the three-flavor probability of electron anti-neutrino survival is:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2(2\theta_{13}) \sin^2 \left[\Delta m_{21}^2 \left(\frac{L}{4E} \right) \right] - \sin^2(2\theta_{13}) \left(\cos^2 \theta_{12} \sin^2 \left[\Delta m_{31}^2 \left(\frac{L}{4E} \right) \right] + \sin^2 \theta_{12} \sin^2 \left[\Delta m_{32}^2 \left(\frac{L}{4E} \right) \right] \right) \quad (2.13)$$

2.2.2 Two Flavor Vacuum Oscillations

In the simplified instance of two neutrino flavors states and two mass states the same probability calculations apply. For this case there is only one mass splitting term and one rotational angle of the mixing matrix.

$$U = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \quad (2.14)$$

The probability for flavor change or survival in this case becomes:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \left[1.27 \Delta m^2 \left(\frac{L}{E} \right) \right] \quad (2.15)$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2 \left[1.27 \Delta m^2 \left(\frac{L}{E} \right) \right] \quad (2.16)$$

Although there are three known neutrino flavor states, under certain conditions the two state approximations can be experimentally applied. Because the magnitude of the terms $\Delta m_{ji}^2 L/E$ are such that,

$$\Delta m_{ij}^2 \frac{L}{4E} \gg \Delta m_{jk}^2 \frac{L}{4E} \quad (2.17)$$

the experiment sensitivity in this approximation will reduce to the two neutrino case [7]. This has been exploited for experiments probing for oscillations such as atmospheric and reactor neutrino sectors. For atmospheric and accelerator experiments (neglecting matter effects) the transition of ν_μ to ν_τ can be expressed:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23}) \cdot \cos^4(\theta_{13}) \sin^2 \left[\Delta m_{32}^2 \left(\frac{L}{4E} \right) \right] \quad (2.18)$$

A small value of θ_{13} makes this transition only dependent the two parameters θ_{23} and Δm_{32}^2 .

For a reactor experiment looking at the survival probability of electron anti-neutrinos for baselines of <5km:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2 \left[\Delta m_{32}^2 \left(\frac{L}{4E} \right) \right] \quad (2.19)$$

2.2.3 Matter Effects

Previous oscillation discussions deal with propagation of neutrinos in a vacuum, which is an acceptable approximation in many cases due to the small cross section of

neutrino interactions. In a denser medium, like the sun or earth, matter effects must be considered due to coherent scattering. Matter is made up primarily of the first generation of standard model particles (i.e. electrons). As neutrinos propagate through matter, weak charge-current interactions impact only electron neutrinos (and antineutrinos). Wolfenstein first proposed this enhancement to neutrino oscillations in 1978 [12]. Mikheev and Smirnov built a framework for the resonant behavior of oscillation based on the neutrino energy, electron density, and vacuum oscillation parameters. Known as the MSW effect, electron neutrinos have an additional potential due to charge current interactions.

$$V_m = \sqrt{2} G_F N_e \quad (2.20)$$

G_F is the Fermi coupling constant and N_e is the electron density. Looking at the two-neutrino case, the propagation becomes:

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \frac{-\Delta m^2}{2E} \cos 2\theta + V_m & \frac{\Delta m^2}{2E} \sin^2 \theta \\ \frac{\Delta m^2}{2E} \sin^2 \theta & \frac{\Delta m^2}{2E} \cos 2\theta - V_m \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad (2.21)$$

where Δm^2 and θ are the vacuum oscillation parameters. Equation 2.11 is rewritten in terms of matter mass eigenstates, ν_{1m} and ν_{2m} , and mixing angle θ_m where:

$$U_m = \begin{bmatrix} \cos \theta_m & -\sin \theta_m \\ \sin \theta_m & \cos \theta_m \end{bmatrix} \quad (2.22)$$

θ_m is defined as:

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{E} \sin 2\theta}{\frac{\Delta m^2}{E} \cos 2\theta - V_m} \quad (2.23)$$

Resonance, where the mixing is maximal, will now occur at:

$$\frac{\Delta m^2}{E} \cos 2\theta = V_m = \sqrt{2} G_F N_e \quad (2.24)$$

The resonance conditions are impacted by both electron density and the energy of the neutrino. The probability of flavor change of the electron neutrinos in matter, for example, becomes:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_m \cdot \sin^2 \left[\Delta m^2 \left(\frac{L}{E} \right) \sqrt{\sin^2 \theta + \left(\cos 2\theta - \frac{2EV_m}{\Delta m^2} \right)^2} \right] \quad (2.25)$$

For a low-density medium, $V_m \approx 0$, equation 2.25 degenerates back to the vacuum probability in equation 2.15. In a medium such as the sun or Earth (for long distances), the MSW effect must be accounted for [13].

Chapter 2.3:

Neutrino Sources

Neutrinos are the most abundant of the known component of matter (mass-less photons excluded) with both naturally occurring and man-made sources. Notable natural sources include the stars, cosmic rays interacting in our atmosphere, radioactive isotopes, supernova events, and “relic” neutrinos from the big bang. With the exception of relic neutrinos, each source has been experimentally detected. Studies of solar and atmospheric neutrinos (discussed in Chapter 3) proved the occurrence of neutrino flavor change and oscillation.

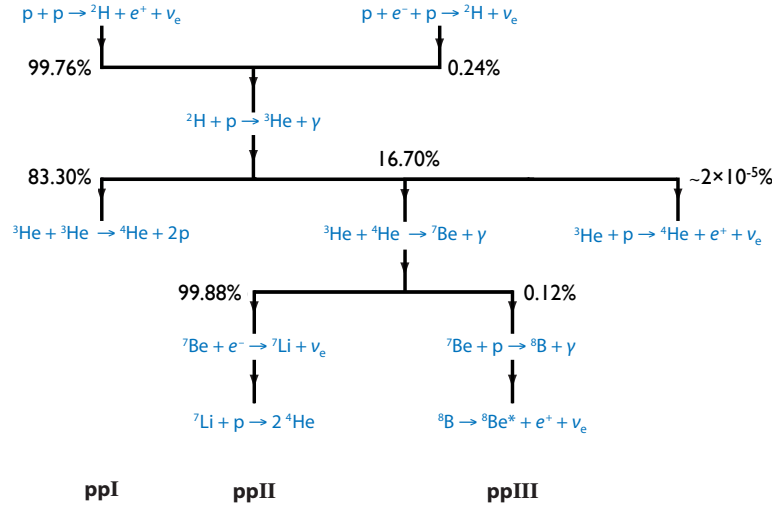


Figure 2.4: PP-chain neutrino producing mechanisms [14].

Solar neutrinos are produced in the pp-chain and CNO-cycle within the core of the sun. The pp-chain and CNO-cycle are competing mechanisms for hydrogen burning within the structures of stars. With the size and temperature of our Sun the pp-chain is dominant producing about 98.5% of neutrinos. The dominant producer is the $p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$ interaction that produce neutrinos with an energy spectrum up to

0.48MeV. Higher energy neutrinos come from pep, Hep, ${}^7\text{Be}$, and ${}^8\text{B}$ interactions and decays (figure 2.4) [14].

Neutrinos originating from the Earth's atmosphere originate from incoming cosmic ray particles. The cosmic ray particles (primarily protons) interact with the atmosphere producing secondary cosmic particles. The resulting secondary π^+ (π^-) decay into u^+ (u^-) and muon neutrinos (anti-neutrinos) (equation 2.26). Muons(+/-) can then decay resulting in electrons (positrons), electron neutrinos (anti-neutrinos) and muon anti-neutrinos (neutrinos) (equation 2.27). The wide energy range of atmospheric neutrinos reaches above hundreds of GeV but peaks around 1GeV [15].

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \quad (2.26)$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu}) \quad (2.27)$$

Geo-neutrinos are electron anti-neutrinos that are produced inside the earth. These are produced from the decay chain of naturally occurring isotopes ^{238}U , ^{232}Th and ^{40}K . As these isotopes undergo β^- decay into stable isotopes electron anti-neutrinos are produced. The geo-neutrinos reach energies up to 3.3MeV (figure 2.5).

Neutrinos can also be produced from man made sources that have been critical to the past decades of neutrino studies. The two most notable sources in experimental studies are from nuclear reactors and accelerator beams but other sources include nuclear explosions and artificial unstable isotopes. Neutrinos from particle accelerators have become a crucial tool in neutrino property studies. The advantages of accelerator beams include flexibility of energy, neutrino flavor selection, timing, and high flux of sources. Typical accelerator neutrino sources are produced from high-energy proton beams. The beams strike a fixed target producing a hadronic shower containing pions and kaons. The decay of the pions and kaons is similar to the neutrino production in the atmosphere. Reactor neutrinos are produced during the β^- decay of nuclear fission products. In chapter 5 details of reactor electron anti-neutrinos are given.

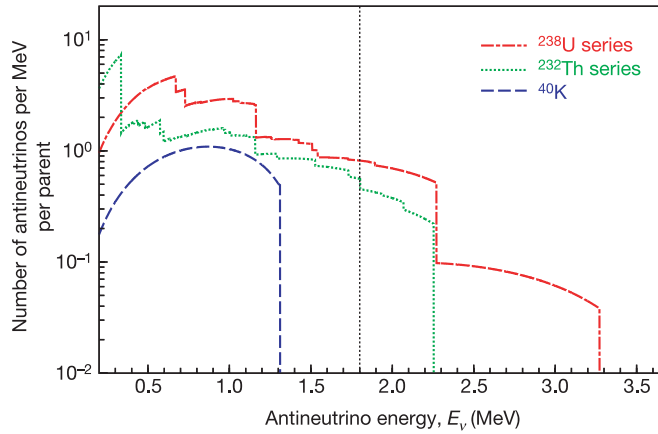


Figure 2.5: Energy spectrum of geo-neutrinos (dotted line is sensitivity limit of for Inverse Beta Decay) [16].

Chapter 3

Experimental History

There has been a robust neutrino experimental history beginning with the first detection of reactor anti-neutrinos in 1956. The progression of neutrino experiments spread to the eventual detection of all three flavors of neutrinos. Neutrino flavor change first appeared in the solar neutrino deficit first seen at the Homestake experiment in the late 1960s. There have been numerous experiments probing neutrino oscillations. From these experiments, most notably KamLAND, there is a clearer picture of the leptonic mixing of neutrino flavor states and mass states described in Chapter 2.2. In this chapter I will describe the evolution of neutrino experiments that have provided the current parameters for neutrino oscillation.

Chapter 3.1

Reines and Cowan

Early neutrino theorist believed that detection of the elusive particles would be unachievable. In 1951, Fredrick Reines set the goal of neutrino detection. Working with Clyde Cowan, the first neutrino detection ideas centered on the large anti-neutrino flux possible from a nuclear explosion. This flux would be great enough to overcome the backgrounds present in the detector technology of the time. A liquid scintillator detector, deployed underground, would measure positron annihilation signals during the first few seconds following the nuclear detonation (Figure 3.1). The positrons are a result of inverse beta decay reactions. Inverse beta decay (IBD) is the weak interaction between an electron anti-neutrino and proton yielding a positron and neutron. The project was initially approved but it became clear the building such a detector in the vicinity of a nuclear test explosion would be too much of a daunting task [17].

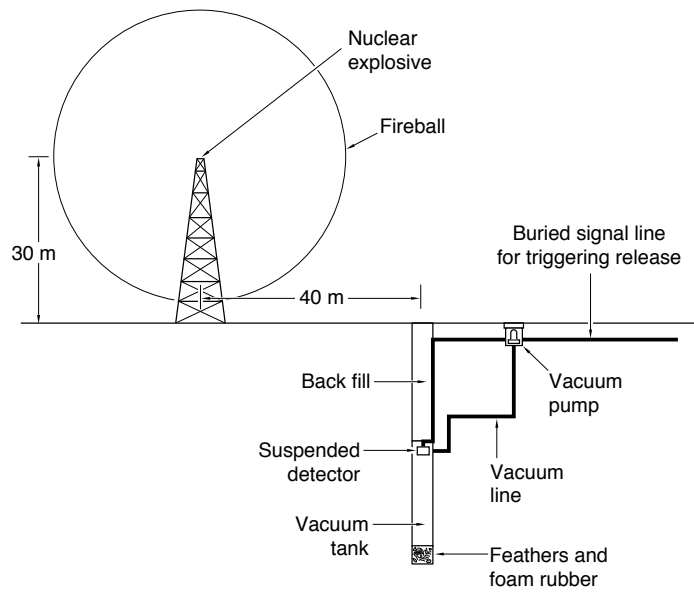


Figure 3.1: Proposal for neutrino detector from nuclear explosion [17]

There was a shift to detecting the anti-neutrino products of nuclear reactors instead of a nuclear explosion. To deal with the lower anti-neutrino flux and backgrounds, the idea of a coincidence signal was envisioned. Instead of just measuring the positron from the IBD interaction, the positron signal would serve as a prompt signal followed by a signal from the capture of the resulting neutron (Figure 3.2). The first experimental attempt was in the proximity of a plutonium-producing nuclear reactor in Hanford, Washington (the largest fission reactor in the United States at the time). The detector, named Herr Auge (Mr. Eye), was a 300-liter tank filled with liquid scintillator surrounded by 90 Photo-Multiplier Tubes (Figure 3.3). This was the largest liquid scintillator detector of the time. The liquid scintillator base of toluene was loaded with Cadmium (as a neutron absorber). After several months of running the results were inconclusive. With the reactor on or off there was a coincidence rate of about 5 counts per minute. The detector was located above ground and it was later realized that the background rates were due to cosmic ray muons. Any future efforts would require detectors that were underground to provide shielding from the cosmic background [17].

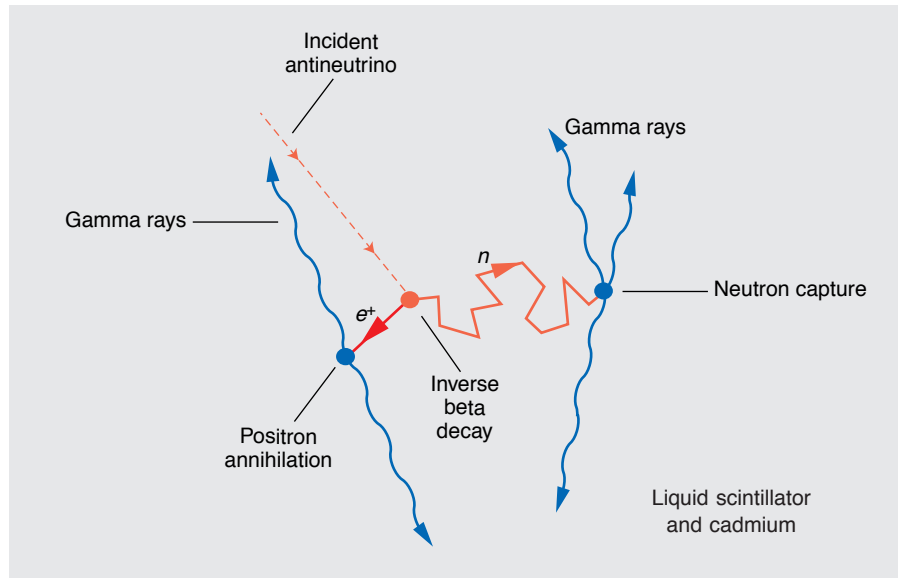


Figure 3.2: The inverse beta decay reaction in the Hanford Experiment detector [17].



Figure 3.3: The Hanford Experiment detector.

The next attempt for neutrino detection came at the Savannah River fission reactor in South Carolina. The detector was located in an underground building of the reactor which provided 12 meters of overburden to shield from muons and hadronic components from cosmic rays. In addition to the underground location, improvements were made to the detector for the selection of the characteristic inverse beta decay signal. There were three tanks 1400-liter tanks of liquid scintillator with 110 photomultiplier

tubes on each tank. Between the scintillator tanks were 200-liter tanks of water loaded with Cadmium to serve as a target (figure 3.4). As an electron anti-neutrino interacts with a proton in one of the water tanks a prompt signal of positron annihilation was detected in the adjacent scintillator tanks. A timer was opened for 30 microseconds searching for the signature signal of a neutron captured on Cadmium (figure 3.5). The detector was deployed in 1955 and in 1956 the detection of anti-neutrinos from fission products was announced with a reaction cross-section which was within 5% of the theory at the time ($6.3 \cdot 10^{-44} \text{ cm}^2$)[18].

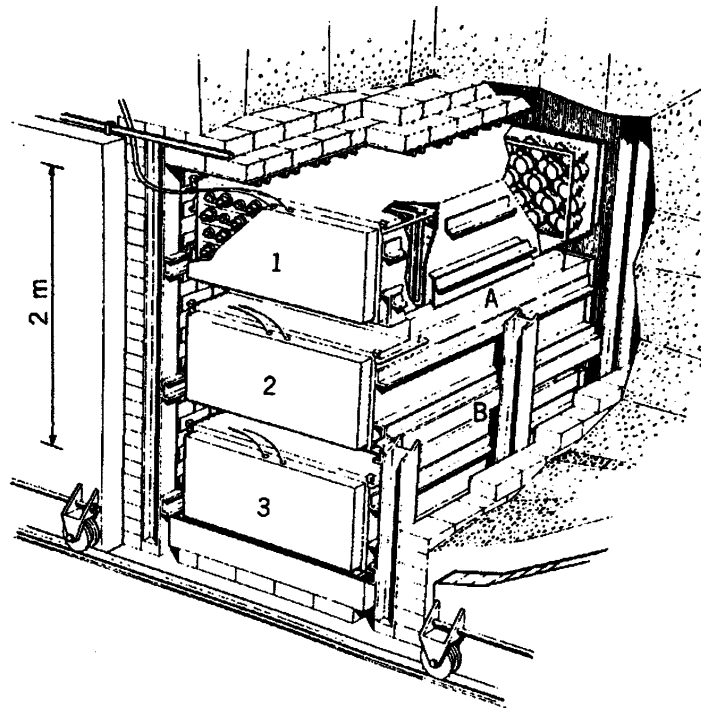


Figure 3.4: Sketch of the detector at the Savannah River site. Areas 1, 2, and 3 are the liquid scintillator tanks. Areas A and B are Cd loaded water.[18].

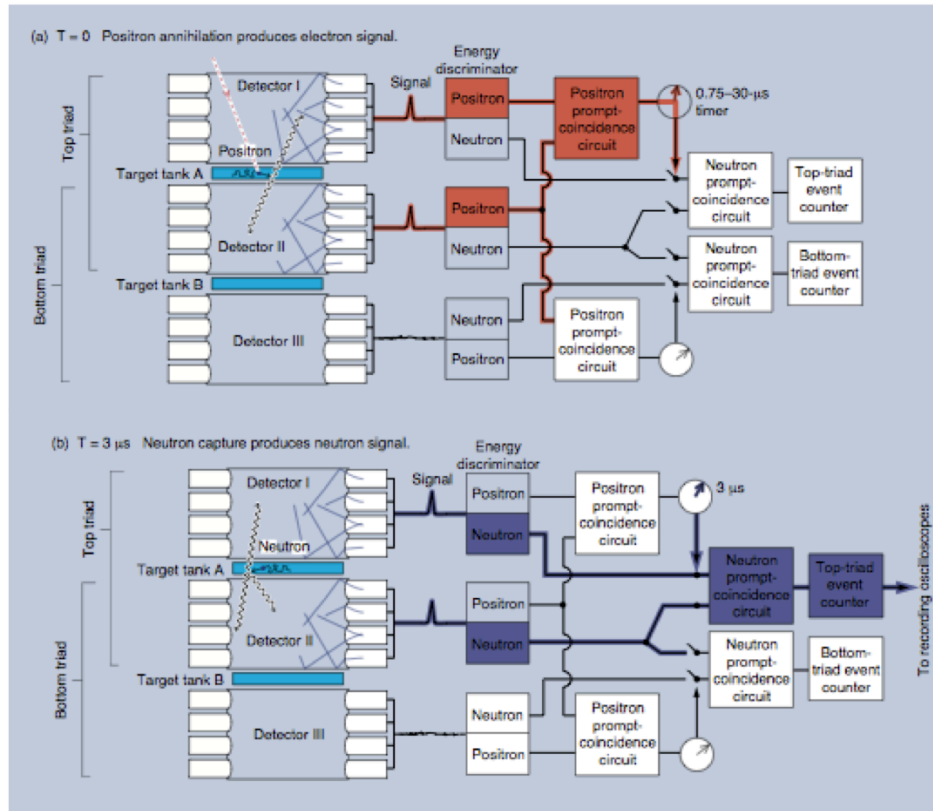


Figure 3.5: The characteristic prompt and delay signal from the Savannah River detector [17].

Chapter 3.2

Solar Neutrinos

The first indications of neutrino flavor change came from the “solar neutrino problem”. This “problem” was the discrepancy between the standard solar model predictions of neutrinos produced in the sun and the experimentally measured flux. The neutrinos produced in the sun are all electron neutrinos. Early experiments were only sensitive to the detection of the electron neutrinos and showed only a fraction of predicted values. This detected deficiency was the experimental focus of several projects spanning over four decades.

3.2.1 Homestake Solar Neutrino Detector

In 1965-1967 an experiment was built in the Homestake mine in North Dakota to detect the solar neutrino flux. Ray Davis envisioned the experiment based on solar models. To detect the solar electron neutrinos, the inverse beta decay reaction



was exploited. The threshold for neutrino detection of this radiochemical method is 0.814 MeV [19]. This sensitivity would allow for the detection of solar neutrinos produced by ${}^7\text{Be}$ (electron capture) and ${}^8\text{B}$ (beta) decay in the pp fusion chain (figure 3.6). This deep underground experiment had 4200 meters water equivalent to shield from the cosmic muons, the largest contribution to backgrounds. The detector was a large tank containing 615 metric tons of tetra-chloroethylene (C_2Cl_4). Argon gas, produced via electron neutrino interactions, was extracted from the tank into a proportional counter. The ${}^{37}\text{Ar}$, having a half-life of 35 days, electron capture decay would be measured to determine the production rate in the tank (figure 3.7). The initial results in 1968 showed a deficit in the detected number of solar by a factor of ~ 7 as compared to the solar theories [20]. Detector upgrades were implemented to increase the background suppression and the experiment ran from 1970 – 1994. The data over the 24 years of running gave an average neutrino capture rate of $2.56 \pm 0.16(\text{stat}) \pm 0.16(\text{syst})$ SNU (figure 3.8). SNU is defined as 10^{-36} interactions per target atom per second. This result was on $\sim 30\%$ of standard solar models, which ranged from 6.36 SNU to 9.3 SNU [19].

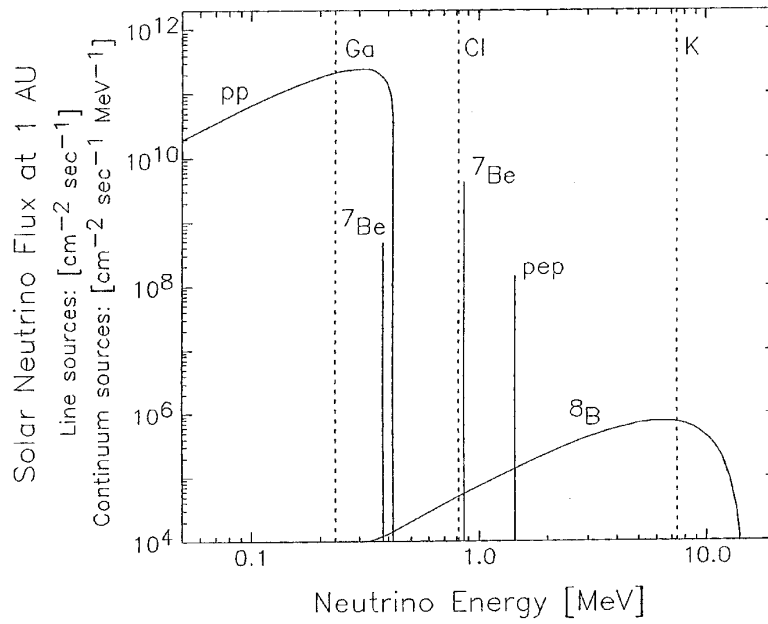


Figure 3.6: Solar neutrino energy spectra in the pp-chain. [21]

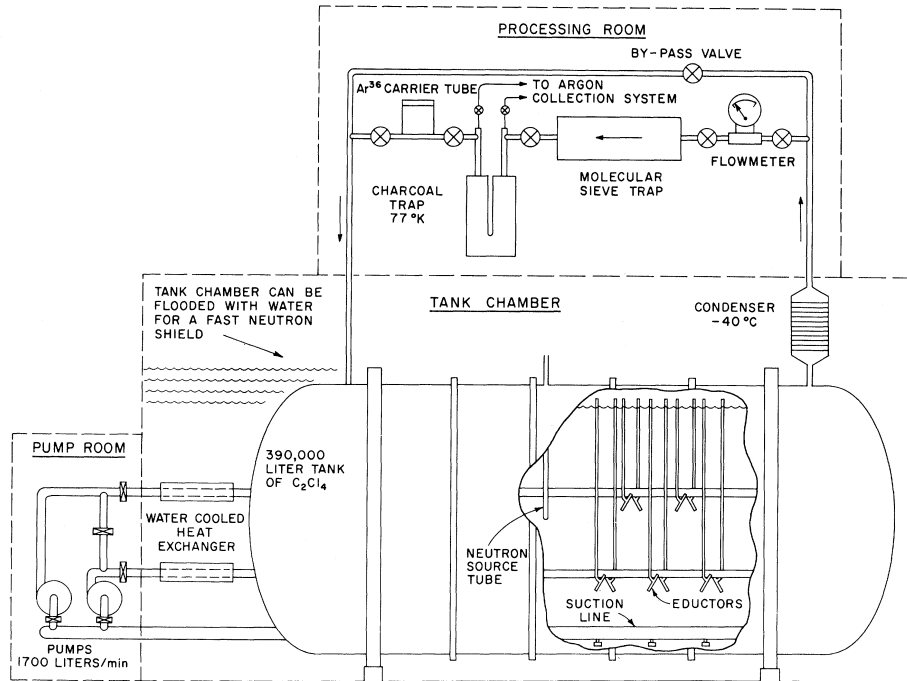


Figure 3.7: Schematic of the Homestake solar neutrino detector [20]

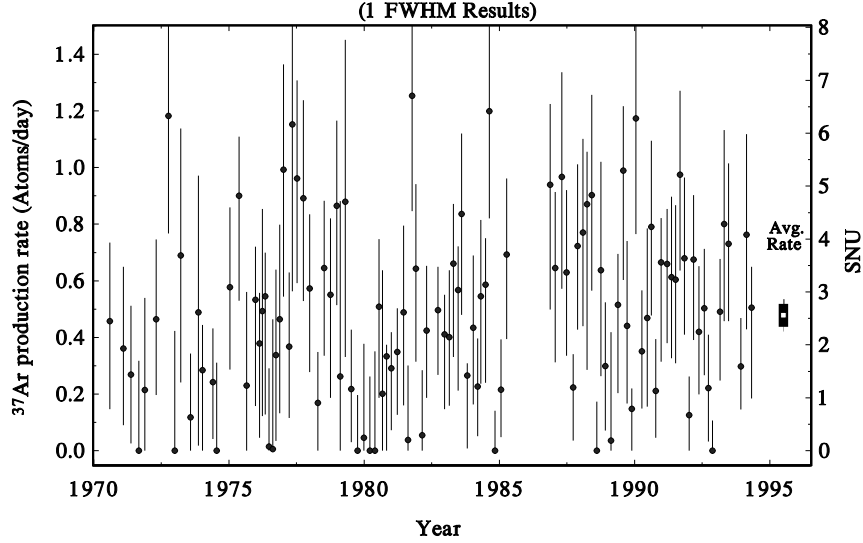


Figure 3.8: Homestake Experiment ^{37}Ar production rate, 1970-1994 [19]

3.2.2 Kamiokande and Super-Kamiokande

During the long run of the Homestake mine experiment, there was separate confirmation of the deficiency of solar neutrinos measured at the Kamiokande-II detector. Kamiokande was a large water Cherenkov detector located in the Kamioka zinc mine in Japan. In this Cherenkov detector, neutrino arrival time, direction, and energy spectrum are measured via neutrino-electron scattering. Elastic scattering involved the exchange of a Z boson (for all neutrino flavors) or a W boson (for electron neutrino flavors only). The interaction:

$$\nu + e^- \rightarrow \nu + e^- \quad (3.2)$$

scatters electrons to speeds greater than the phase velocity of light, in the 2142 metric tons of purified water, which produces Cherenkov light cones. These cones were detected by a sample of the 948 photo-multiplier tubes surrounding the walls of the water tank. Event reconstruction of the light cones allows for directional and energy information of the scattered particles in addition to particle identification (i.e. electron or muon). The energy threshold was set at 9.3 MeV the first 450 days of running and 7.5 MeV for 590 days of running from January 1987 through April 1990. This threshold set

Kamiokande only sensitive to the higher energy neutrinos produced by ^8B decay (figure 3.5). The ratio of the measured flux of ^8B electron neutrinos to the predictions of solar models was $0.46 \pm 0.13(\text{stat}) \pm 0.08(\text{syst})$ (figure 3.9) [22].

In the same mine as the original Kamiokande detector an even larger detector was built at the end of 1995. Named Super-Kamiokande (SK), it is a 50,000 ton Cherenkov water detector. The detector was made to detect solar, atmospheric (discussed in Section 3.3) and long-baseline accelerator neutrinos. The first phase (SK-I) of running netted 1678 live-days of solar data between April 1996 and July 2001. Along with the greater volume then the original Kamiokande, the PMT coverage was increased to 40.4% using 11,146 20 inch photo-multiplier tubes. As in its predecessor, the detection of solar neutrinos was via the elastic scattering of electrons. The threshold of Super-Kamiokande was at 6.5MeV making it sensitive to the ^8B solar neutrinos. The precision and large data

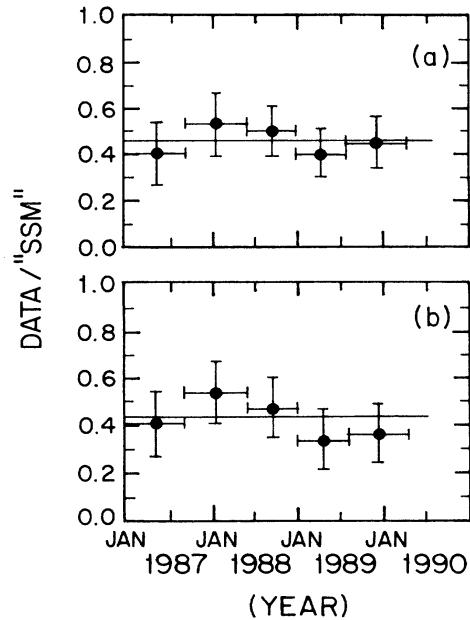


Figure 3.9: The Kamiokande-II neutrino flux data/SSM (standard solar model prediction) (a) 9.3MeV threshold for first two points and 7.3MeV threshold for last three points. (b) all with 9.3MeV threshold [22].

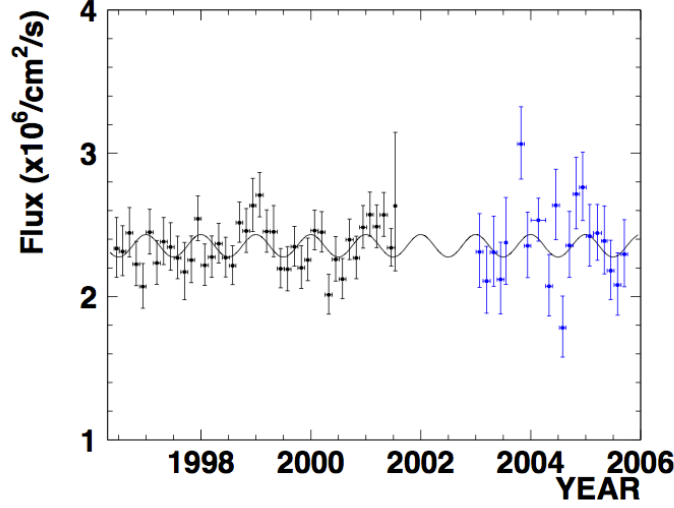


Figure 3.10: SK-I (black) and SK-II (blue) solar neutrino flux. The solid line represents the fluctuation expected due to the seasonal variation of the distance between the Earth and Sun [24].

set of the SK-I allowed for measurements of the neutrino energy spectrum, day-night variations, and seasonal variations along with the overall neutrino flux. The measured flux at Super-Kamiokande (SK-I) phase one was $2.35 \pm 0.02(\text{stat}) \pm 0.08(\text{syst}) * 10^6 \text{cm}^2 \text{s}^{-1}$ [23]. A second phase, Super-Kamiokande II (SK-II), of data taking followed an accident in which many SK photo-multiplier tubes were lost. SK-II had a live time of 791 days between December 2002 and October 2005. The flux results for SK-II were $2.38 \pm 0.05(\text{stat})^{+0.16}_{-0.15}(\text{syst}) * 10^6 \text{cm}^2 \text{s}^{-1}$ (figure 3.10) [24]. Both SK results were consistent with the results from Kamiokande-II yielding just over 40% of the predicted solar models. This higher yield of neutrinos as compared with the Homestake results can be accounted for in the fact that SK has a small sensitivity to other neutrino flavors.

3.2.3 Gallium Solar Neutrino Experiments

Due to the energy thresholds, solar neutrino experiments were only sensitive to the neutrinos produced by ^8B and ^7Be (for Homestake only). A series of new radio-chemical experiments were proposed in order to reach lower thresholds. The lower thresholds would be achieved by the use of ^{71}Ga as a target for the interaction that

produced ^{71}Ge . The threshold for this interaction was .233keV allowing for detection of neutrinos produced in pp reaction [25]. Three notable Gallium experiments were GALLEX, GNO and SAGE.

GALLEX, located in the Gran Sasso Underground Laboratory in the Italy, had three periods of running which ended in October 1995. GALLEX detector housed 30.3 tons of $\text{GaCl}_3\text{-HCL}$ solution. The inverse beta decay reactions with solar electron neutrinos produced GeCl_4 . These compounds were extracted from the tanks and proportional counters would determine the ^{71}Ge production from its radioactive decay. 53 runs from 1991-1995 yielded a neutrino rate of $69.7^{+7.8}_{-8.1}$ SNU (figure 3.11). This result showed a deficit between 51 and 61% of the solar models [25].

The GNO experiment was the next phase of GALLEX. Improvements were made in the counting efficiency and event selections. GNO ran in three phases between 1998 and 2003 (figure 3.12). The result for the neutrino rate of GNO was $62.9^{+6.0}_{-5.9}$ SNU [26].

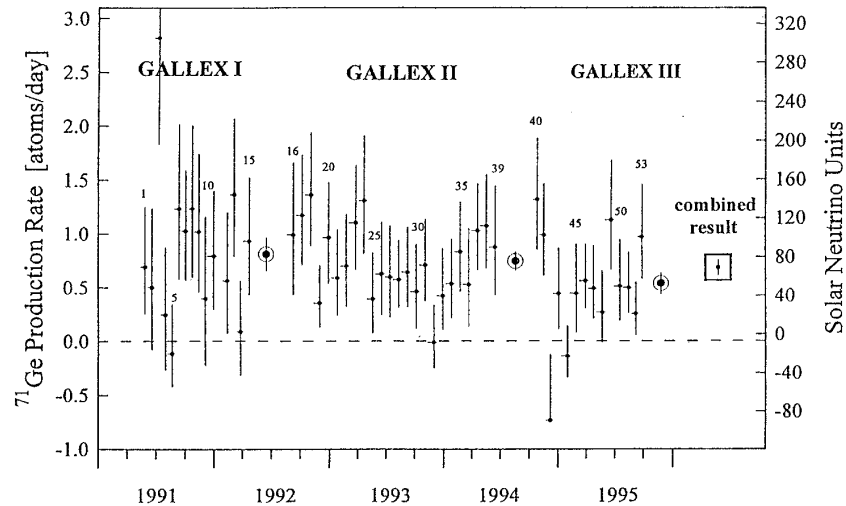


Figure 3.11: ^{71}Ge production in the GALLEX experiment [25]

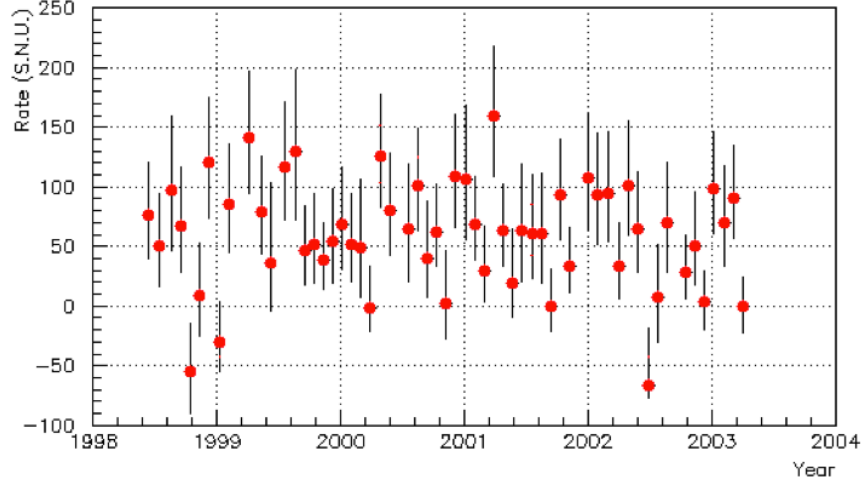


Figure 3.12: Capture rate for the GNO experiment [26]

The SAGE Collaboration was the Russian-American effort to measure solar neutrino capture on gallium. The experiment was located at the Baksan Neutrino Observatory in the northern Caucasus Mountains. SAGE used 50 tons of gallium in its liquid metal form as a target. Similar to GALLEX, the resulting ^{71}Ge is extracted into a proportional counter. The decay of the ^{71}Ge gives the production rate in the detector. The result of 92 runs between 1990 and 2001 was a rate of $70.8^{+5.3}_{-5.2} \text{ (stat.) } ^{+3.7}_{-3.2} \text{ (syst.)}$ SNU (figure 3.13) [27]. There was agreement from the three Gallium experiment results, which detected a neutrino rate that was roughly 55% of the Standard Solar Model predictions [26].

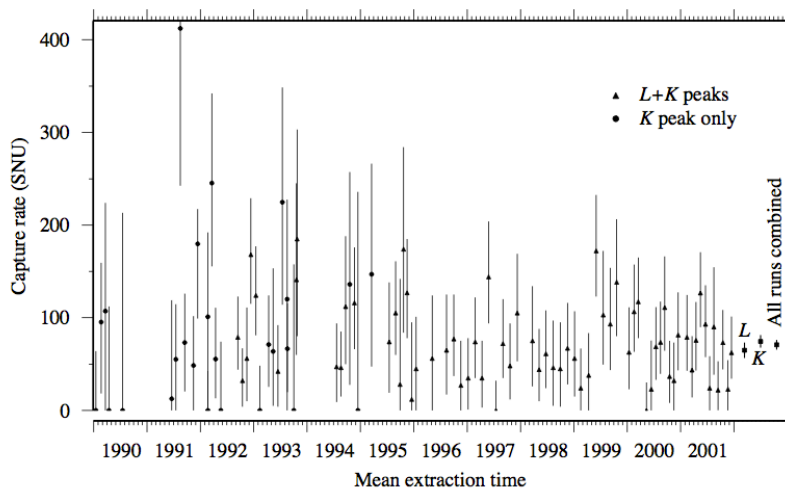


Figure 3.13: Capture rate for the SAGE experiment [27]

3.2.4 SNO

Each of the mentioned solar neutrino experiments were primarily sensitive to electron neutrinos via inverse beta decay for radio-chemical experiments and electron scattering for the Cherenkov detectors (Kamiokane and SK had some sensitivity to other flavors as well). Since there were no adjustments that could be made to the standard solar model to account for the deficiency, it was theorized that the neutrinos had oscillated into different neutrino flavors that were not counted in previous experiments experimentally. The Sudbury Neutrino Observatory (SNO) was designed to be sensitive to three flavors of neutrinos and was able to provide an answer to the “solar neutrino problem”.

SNO was a Cherenkov water detector, same as used in Kamiokande and Super-Kamiokande, but used heavy water (D_2O). The design of SNO was such that it could not only detect the elastic scattering of electrons via neutrino interaction but also the charge current and neutral current interactions. Charge current interactions were only sensitive to electron neutrinos. The neutral current interactions

$$\nu_x + d \rightarrow \nu_x + n + p \quad (3.3)$$

are sensitive to all neutrino flavors (ν_x). The ability to measure all neutrino flavors would be confirmation that a fraction of the electron neutrinos produced in the sun arrive at Earth as other flavors. SNO was built in the Inco Creighton mine near Sudbury in the Ontario province of Canada. The detector (figure 3.14) consists of a transparent inner sphere that housed the 1kt of heavy water surrounded by an outer sphere filled with purified water and photomultiplier structure. The geodesic structure held 9438 inward-facing PMTs.

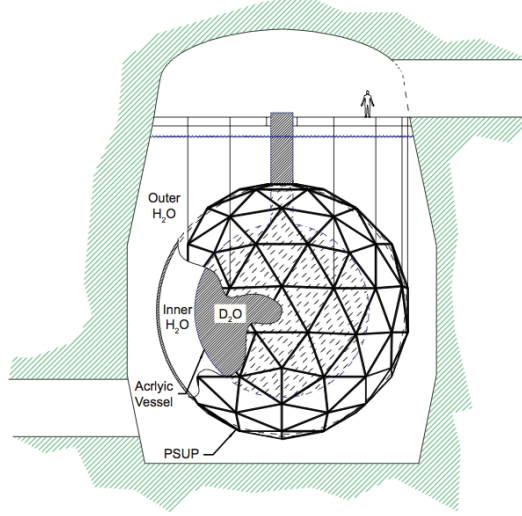


Figure 3.14: Diagram of the SNO detector with an inner volume of heavy water surrounded by light water and PMT structures [28].

The first phase of SNO began in November 1999 and ran until May 2001. This data set represented 306.4 live days. The differences in flux from the charge current and elastic scattering (figure 3.15)

$$\begin{aligned}\phi_{CC} &= 1.76^{+0.06}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \\ \phi_{ES} &= 2.39^{+0.24}_{-0.23}(\text{stat.})^{+0.12}_{-0.12}(\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \\ \phi_{NC} &= 5.09^{+0.44}_{-0.43}(\text{stat.})^{+0.46}_{-0.43}(\text{syst.}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}\end{aligned}$$

were consistent with the differences seen between the radio-chemical and Cherenkov experiments. The most important flux, from the neutral current interactions, finally showed results that were expected by the solar models. This result confirms that the solar neutrinos do oscillate from electron neutrinos. From these interaction fluxes it was determined that the number of electron neutrinos at the surface of the earth was roughly 1/3 of the total neutrinos detected [28].

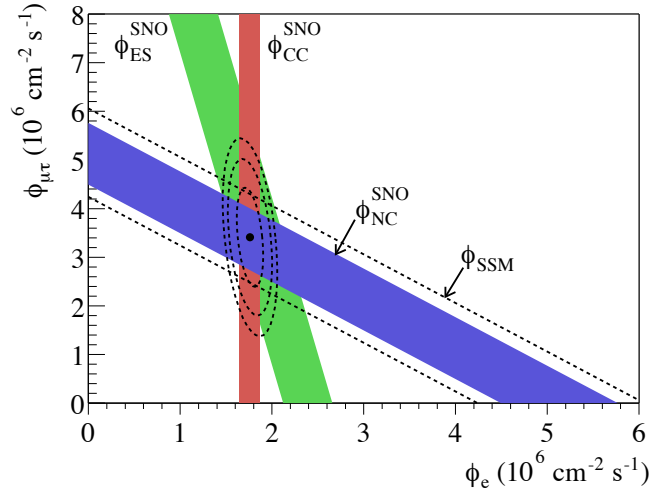


Figure 3.15: The flux electron neutrinos versus the combined flux of muon and tau neutrinos deduced from each of the interactions of SNO phase one (red – charge current, green – elastic scattering, blue – neutral current). Dotted lines are the standard solar model predictions. [28].

SNO ran a second phase from June 2001 – October 2003 with improvements to the neutron capture with the addition of NaCl to the heavy water detector. For the “salt phase” 2000kg of NaCl was dissolved in the D₂O. The enhancements improved the efficiency of neutron capture, increased the total gamma ray production giving a more isotropic the PMT hit pattern. These improvements allowed for better separation of Neutral Current interactions. The second phase banked 391.4 live days of data and the flux measurements of each interaction were similar to that of the first data set (below units are $10^6 \text{ cm}^{-2} \text{ s}^{-1}$)

$$\begin{aligned}\phi_{\text{CC}}^{\text{uncon}} &= 1.68_{-0.06}^{+0.06}(\text{stat})_{-0.09}^{+0.08}(\text{syst}) \\ \phi_{\text{ES}}^{\text{uncon}} &= 2.35_{-0.22}^{+0.22}(\text{stat})_{-0.15}^{+0.15}(\text{syst}) \\ \phi_{\text{NC}}^{\text{uncon}} &= 4.94_{-0.21}^{+0.21}(\text{stat})_{-0.34}^{+0.38}(\text{syst})\end{aligned}$$

The neutral current interactions flux was again consistent with solar model data (Figure 3.16) [29].

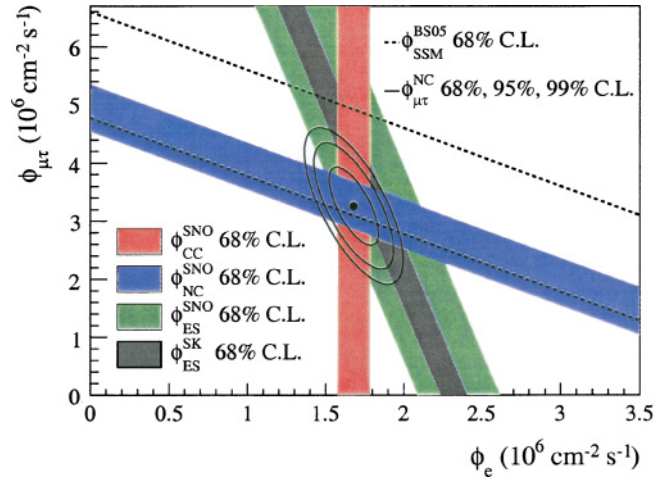


Figure 3.16: The flux electron neutrinos verses the combined flux of muon and tau neutrinos deduced from each of the interactions of SNO phase two (red – charge current, green – elastic scattering, blue – neutral current, gray – SK results). Dotted lines are the standard solar model predictions. [29].

The third phase of SNO ran from November 2004 to November 2006 with a 385.17 live day data set. For Phase-III the NaCl was removed from the target and an array of ^3He proportional counters were added for a more precise measurement of the neutral current interactions. The flux measurements for the three interactions during the third SNO phase are (below units are $10^6 \text{ cm}^{-2} \text{ s}^{-1}$)

$$\phi_{\text{CC}} = 1.67^{+0.08}_{-0.09}$$

$$\phi_{\text{ES}} = 1.77^{+0.26}_{-0.23}$$

$$\phi_{\text{NC}} = 5.54^{+0.48}_{-0.46}$$

The results from the final phase of SNO were again consistent with previous data sets and more importantly the Standard Solar Models. The ratio of charged current flux (electron neutrinos only) to the neutral current flux (all neutrino flavors) was 0.301 ± 0.033 . [30].

3.2.5 Global Solar Results

Results from SNO provided resolution to the over 30 year old solar neutrino problem. Originating as electron neutrinos, roughly one third of the solar neutrinos arrive to Earth in their original flavor state. A comparison of the measured neutrino flux to Standard Solar Model BS05(OP) is shown in Figure 3.17. It is worth note that the discrepancy between Gallium experiments to Homestake and SNO is understood within the MSW effect. Gallium experiments operate at such a lower threshold that they are sensitive to pp neutrinos. For the lower energy neutrinos the strength of the matter oscillations is lowered (see Chapter 2.2).

Combining data from all the solar neutrino experiments, solar oscillation parameters could be extracted. A two-neutrino approximation is used with the rate data along with day night variations from SK and SNO. In the models neutrinos are propagated out of the Sun, in a vacuum and through the Earth. The mixing parameters were found to be:

$$\Delta m_{21}^2 = 4.90_{-0.93}^{+1.64} \times 10^{-5} eV^2$$
$$\theta_{12} = 34.4_{-1.2}^{+1.3} \text{ deg}$$

The confidence level contours of the solar oscillation parameters are given shown in figure 3.18 [30].

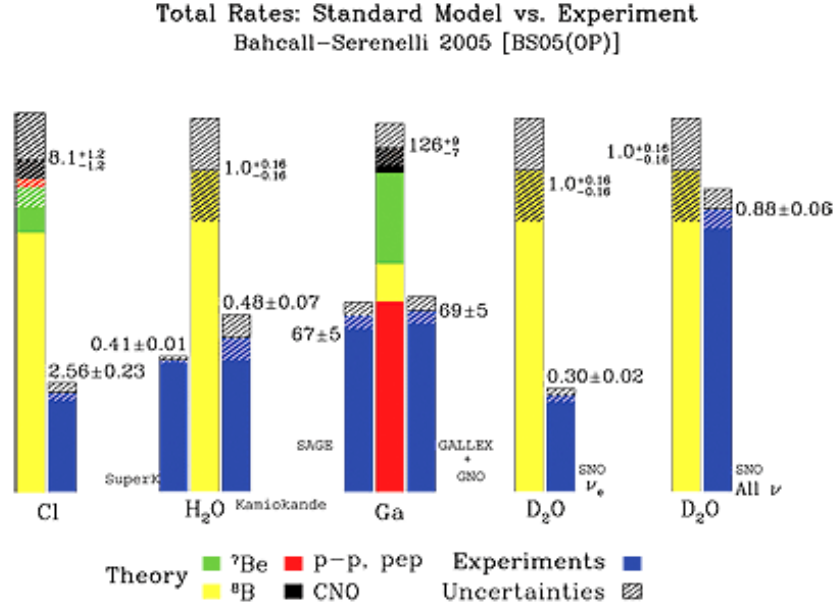


Figure 3.17: Comparison of observed neutrino flux and theoretic values from SSM BS05. Units for Cl and Ga experiments are SNU and Units for Kamionkande, SK, and SNO are ratios of fluxes to SSM [31].

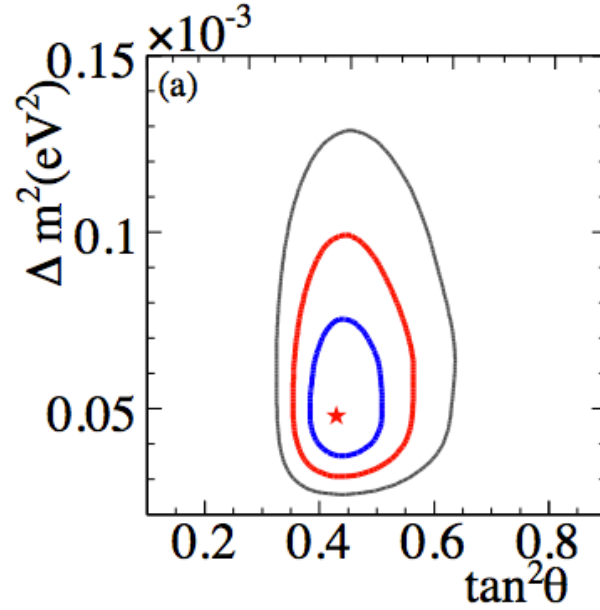


Figure 3.18: Confidence level contours of oscillation parameter for Super-Kamiokande and SNO solar data. Blue – 68% CL, Red – 95% CL, Grey – 99.73% CL[30].

Chapter 3.3

KamLAND

At the site of the original Kamiokande experiment the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) was built. KamLAND's original purpose was the probing the survival probability of electron anti-neutrinos from the 55 nuclear reactors operating in Japan. Inside the KamLAND detector a 13m-diameter nylon balloon houses 1kton of purified liquid scintillator, which serves as both target and detector. An 18m diameter steel vessel that is filled with non-scintillating oil surrounds the target to protect from outside radiation reaching the target area. 1879 PMTs are mounted around the steel structure and provide 34% coverage of the target. The detector lab is 2700m.w.e underground to shield from cosmic-ray moun. A water Cherenkov outer detector is used to tag moun events inside the detector that can produce background events (figure 3.19). The products of inverse beta decay (IBD) interactions provide the signals for incident electron anti-neutrino events, the same interaction detected by the Reines and Cowan experiments. The prompt signal of the positron annihilation and is followed by a delay signal of the neutron capturing on hydrogen. The expected prompt signal energy spectrum is directly proportional to the incoming anti-neutrino energy (and the delay signal is ~ 2.2 MeV from neutron capture on hydrogen (figure 3.20) [32].

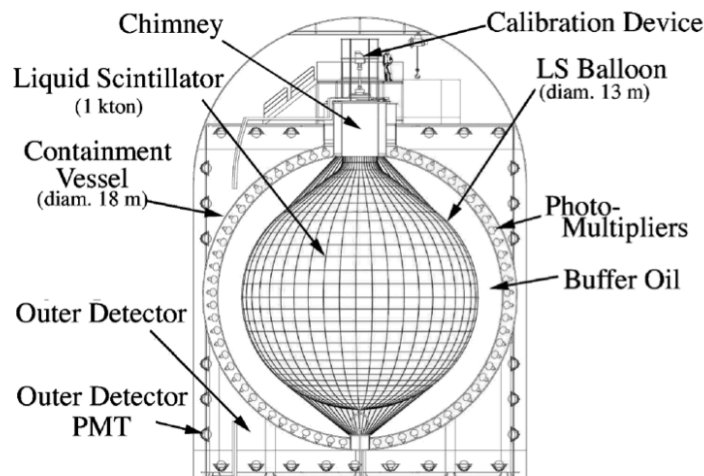


Figure 3.19: Schematic of the KamLAND detector[32].

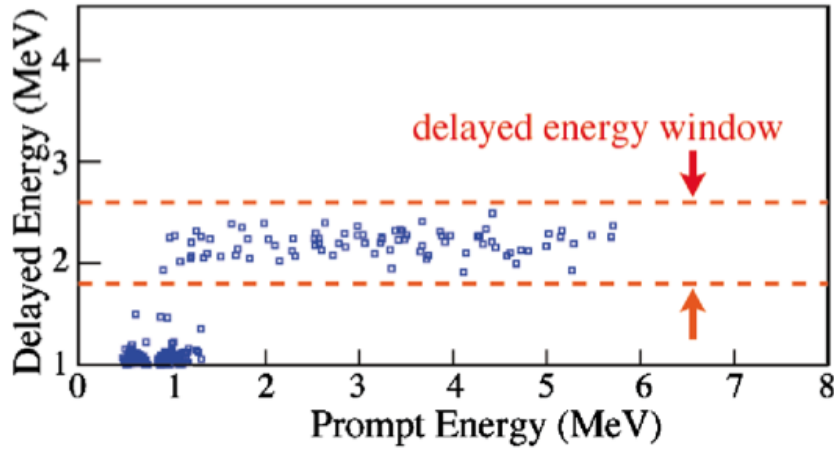


Figure 3.20: Prompt and Delay energy distributions for KamLAND. Neutrino candidates after cuts are between dashed lines [32].

The first reactor neutrino data set was for 141.1 live days recorded March-October 2002. In this data there were 54 events giving a ratio of measured to expected as $0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst})$ (figure 3.21). Along with the deficiency of events the spectral shape of the prompt energy was distorted showing signs of the L/E dependence to oscillations (figure 3.22) [32]. With data taken until May 2007, the results from KamLAND exclude an undistorted spectrum of electron anti-neutrino energy at $>5\sigma$ (figure 3.23).

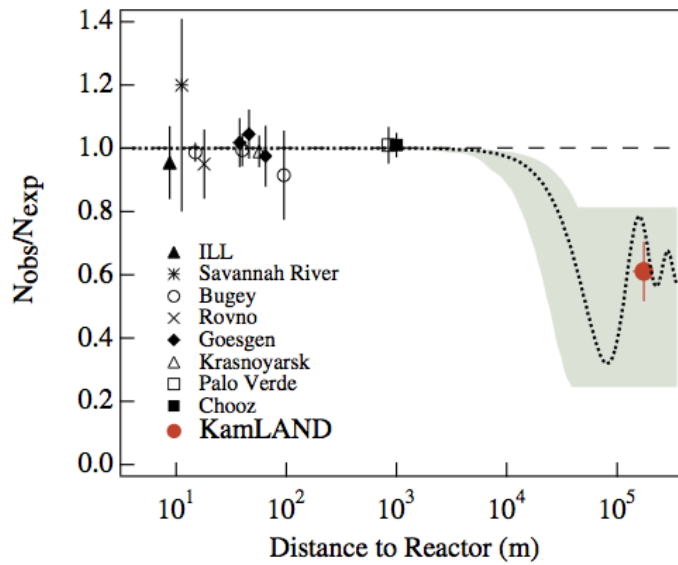


Figure 3.21: Ratio of observed to expected neutrinos for KamLAND first data set. [32].

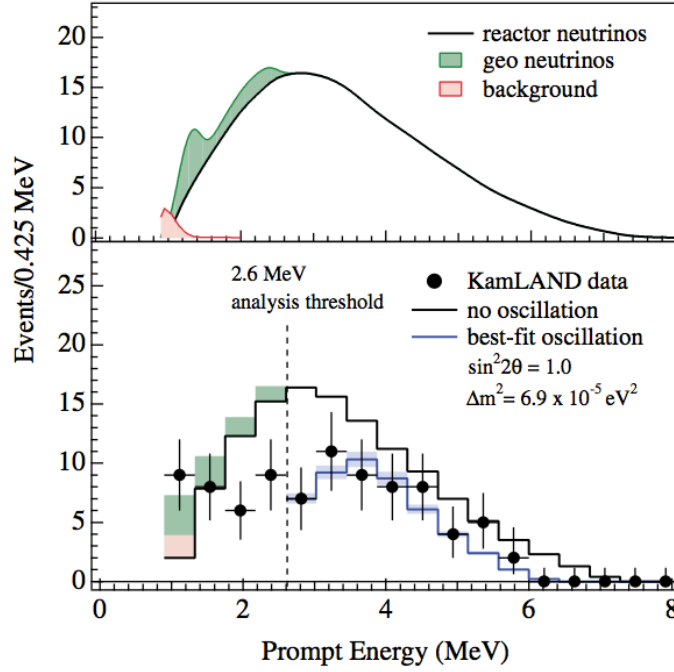


Figure 3.22: Prompt energy spectrum for KamLAND's first results [32].

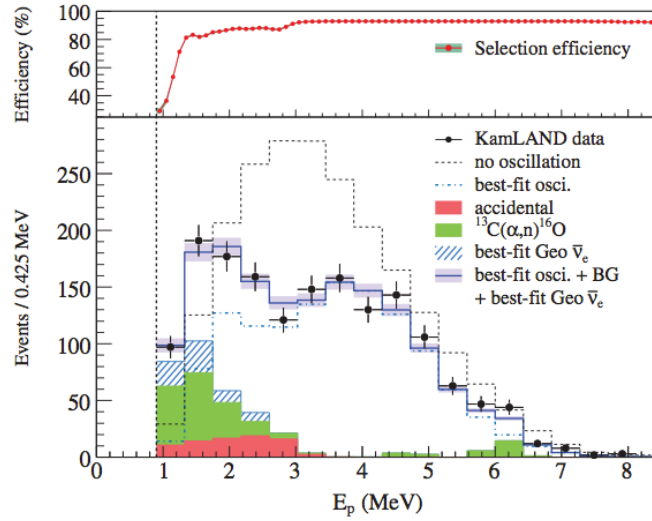


Figure 3.23: KamLAND prompt spectrum for 2.44×10^{32} proton yr data set. [33].

The 55 nuclear reactor anti-neutrino sources are located at an average distance of 180 km from the KamLAND detector. At this distance and energy spectrum of the reactor anti-neutrinos, the survival probability can be treated as the two flavor neutrino

mixing. Two cycles of oscillation can be seen from neutrino energy and distance information (figure 3.24) [33]. KamLAND combined with solar data provided precise values of Δm_{21}^2 and constraints on θ_{12} (figure 3.25). The best-fit values for KamLAND and solar data combined are [33]:

$$\Delta m_{21}^2 = 7.59_{-0.21}^{+0.21} \times 10^{-5} eV^2$$

$$\tan^2 \theta_{12} = 0.47_{-0.05}^{+0.06}$$

In addition to the reactor anti-neutrino measurements, KamLAND has also measured geo-neutrinos [16], solar neutrinos [34] and has begun a campaign of double beta decay, KamLAND-Zen [35].

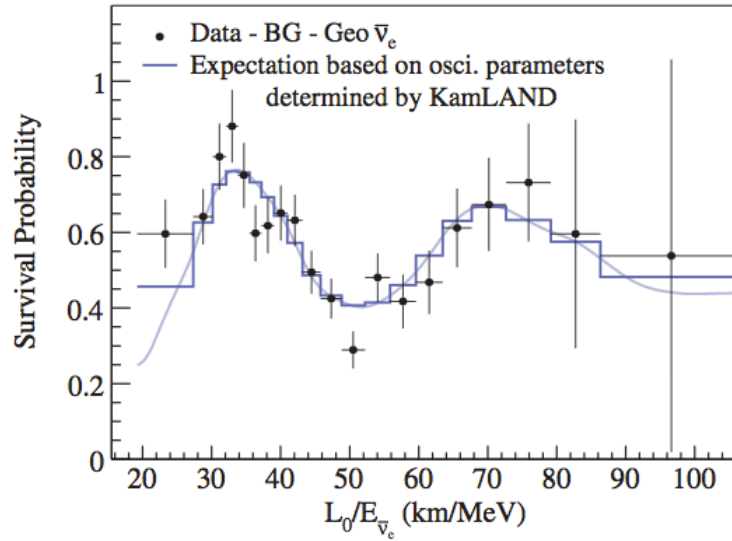


Figure 3.24: KamLAND L/E ratio to the survival probability with oscillation parameters. [33].

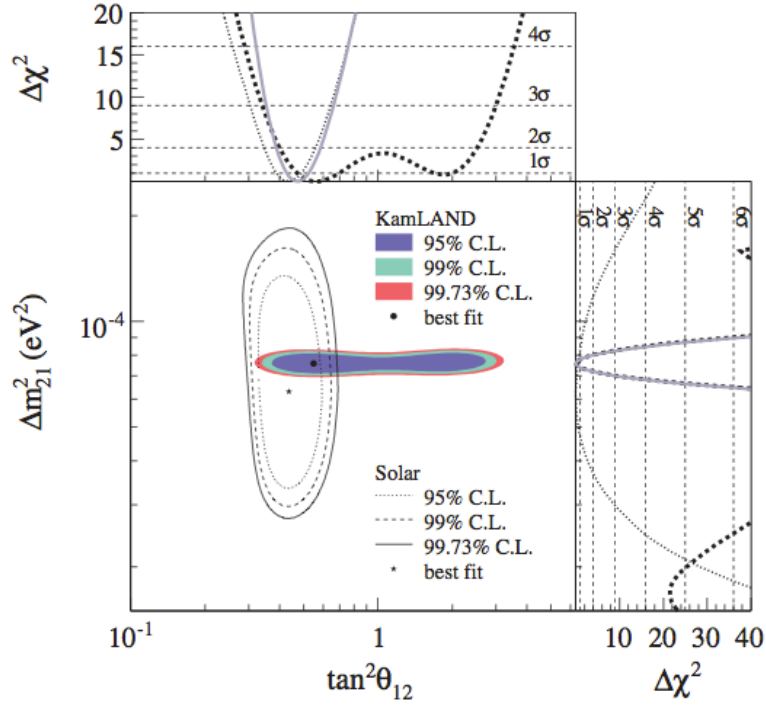


Figure 3.25: KamLAND and Solar data constraints on solar oscillation parameters [33].

Chapter 3.4

Atmospheric Neutrino Oscillations

Chapter 3.4.1 Atmospheric Experiments

As mentioned in Chapter 2.4, neutrinos originate in the Earth's atmosphere from the decay products of hadronic showers (mostly $\pi^\pm$) induced by primary cosmic rays. The cascade of particles resulting from $\pi^+(\pi^-)$ decay will produce a $\mu^+(\mu^-)$ and a muon neutrino (anti-neutrino), the $\mu^+(\mu^-)$ will decay into an $e^+(e^-)$, electron neutrino (anti-neutrino) and a muon anti-neutrino (neutrino). When all decays occur in the atmosphere, the detected flavor ratio of muon neutrinos and anti-neutrinos to electron neutrinos and anti-neutrinos should be ~ 2 (equation 3.4).

$$R \equiv \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \quad (3.4)$$

As neutrino energy rises above $\sim 1\text{GeV}$ the ratio will increase as the neutrinos become relativistic. The incoming cosmic rays have an isotropic distribution in the Earth's atmosphere resulting in an isotropic source of neutrinos. Neutrinos arriving directly downward to the surface have a flight path of $\sim 15\text{km}$ and those arriving upward have a flight path of $\sim 13,000\text{km}$ traversing through the Earth. In the absence of oscillations, the ratios of μ -like neutrinos to e -like neutrinos should have up-down symmetry [15]. Detection neutrinos and their corresponding flavor can be achieved with water Cherenkov detectors. Charge current interactions of incoming ν_μ and ν_e particles produce muons and electrons. The ring of light detected from the Cherenkov cones allow for the identification of type, energy, and direction of the produced particle.

The Kamiokande experiment (described in the Chapter 3.2) was able to probe atmospheric neutrinos with a data set of 4.92 kt yr [36]. A deficiency of muon type neutrinos was found from the ratio described in equation 3.4:

$$\frac{R_{data}}{R_{MC}} = 0.60_{-0.06}^{+0.07} (stat.) \pm 0.05 (syst.)$$

The deficiency was seen in the number of muon neutrinos but no significant reduction in electron neutrinos was measured (figure 3.26).

A muon neutrino deficiency only hints to a transition of muon neutrinos to tau neutrinos. The transition probability can be expressed in the simplified two-flavor case:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left[\Delta m_{32}^2 \left(\frac{L}{4E}\right)\right] \quad (3.5)$$

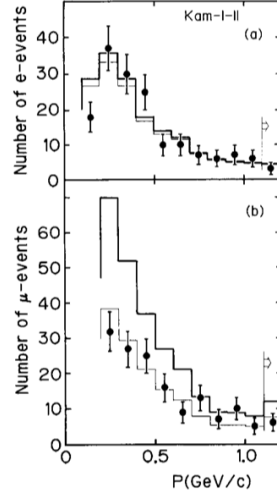


Figure 3.26: Momentum spectrum of e-like and μ -like events for Kamiokande.
Black histogram is MC prediction [36].

Super-Kamiokande, with higher statistics and improved resolution, was able to confirm muon neutrino oscillations. The 33.0 kton yrs of data was separated in to sub-GeV and multi-GeV ranges. For both data sets there continued to be a reduced value for the ratio of data to MC for R (equation 3.4) shown in table 3.1. Asymmetry between up-down muon neutrinos rates was clearly present (figure 3.27) in the zenith angle distributions. Fitting the data to oscillation parameters gives values of $\sin^2(2\theta) > 0.82$ and $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3} \text{ eV}^2$ [37]. The confidence level contours are shown in figure 3.28.

Table 3.1: Summary of event sample and MC for Super-Kamiokande [37].

	Data	Monte Carlo
Sub-GeV		
Single-ring	2389	2622.6
e -like	1231	1049.1
μ -like	1158	1573.6
Multi-ring	911	980.7
Total	3300	3603.3
$R = 0.63 \pm 0.03 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$		
Multi-GeV		
Single-ring	520	531.7
e -like	290	236.0
μ -like	230	295.7
Multi-ring	533	560.1
Total	1053	1091.8
Partially contained	301	371.6
$R_{\text{FC+PC}} = 0.65 \pm 0.05 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$		

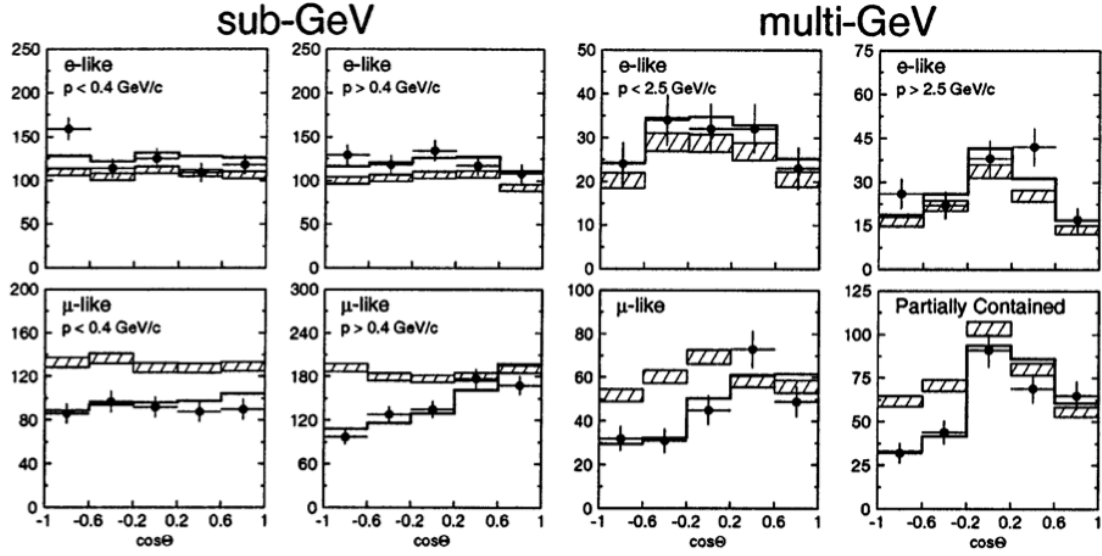


Figure 3.27: The zenith angle distribution of rates for e-like and μ -like events for SK.

For upward particles $\cos\Theta < 0$ and downward particles $\cos\Theta > 0$. Solid lines are best fit oscillation parameters. Hatched regions are expectations for no oscillations.[37].

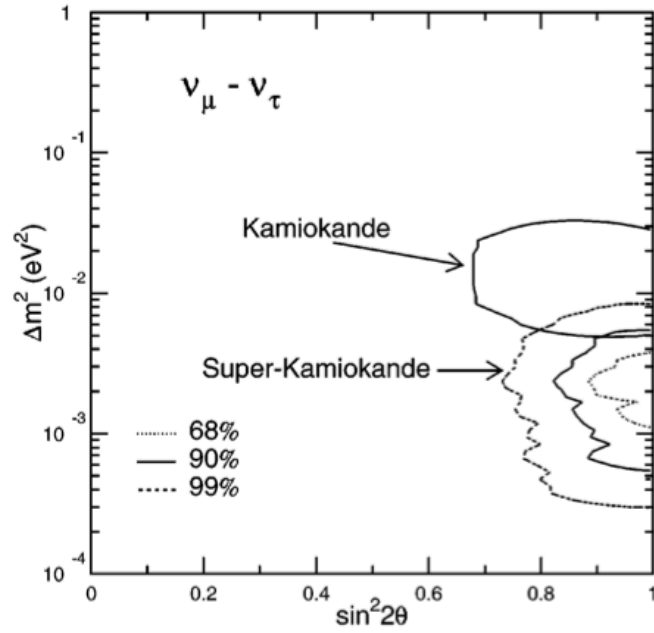


Figure 3.28: Confidence level contours for atmospheric oscillation parameters for SK [37].

Chapter 3.4.2 Accelerator Experiments

Neutrinos produced from collisions of accelerator beams on a target provided the opportunity to measure the atmospheric neutrino oscillations. The K2K experiment was designed to confirm the findings of the findings of Super-Kamiokande. The SK detector was utilized to measure the muon neutrino flux from the KEK accelerator beam. KEK accelerator, in Tsukuba city Japan, is a 12 GeV proton source that strikes an aluminum target resulting in a beam of π^+ . The pions are focused and decay into muons and a beam of neutrinos at 1.0-1.5 GeV mean energy. The neutrino beam travels through the Earth 250km to the SK detector. The muon neutrinos are detected at SK via charge-current interactions. For data taken from June 1999 to November 2004 there were 112 events of the 158 expected [38]. A distortion in the reconstructed neutrino energy was observed (sample of events in figure 3.29) confirming the oscillation results of atmospheric neutrino experiments. The contours of allowed regions for K2K (figure 3.30) were compatible with the SK results.

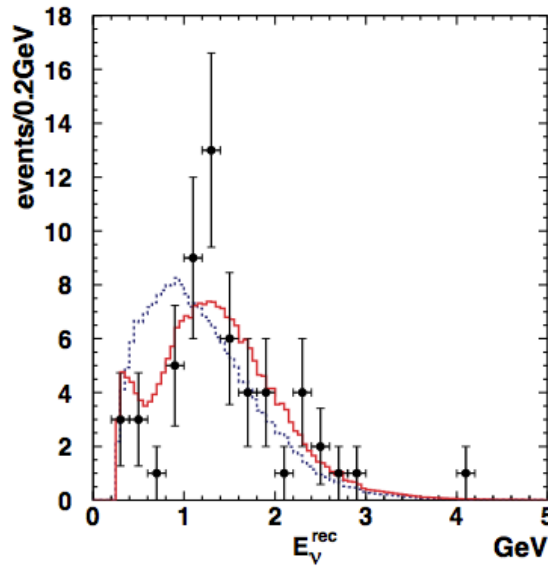


Figure 3.29: E_v distribution for K2K single ring muon like event sample. Blue dotted line is no oscillation expectation and red line is the spectrum for the best fit of oscillation [38].

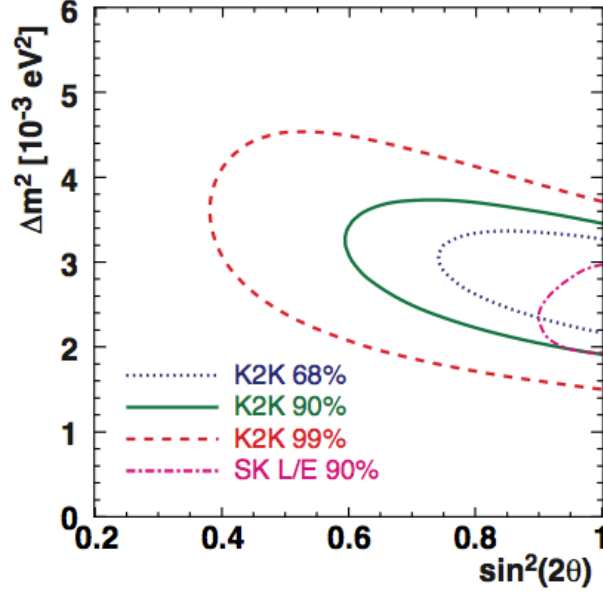


Figure 3.30: Comparison between contours of allowed regions of atmospheric oscillation parameters for K2K and SK [38].

More recently results from the accelerator neutrino experiment MINOS [39] provided the most precise measurement of the atmospheric neutrino oscillation parameters. The Neutrinos at the Main Injector (NuMI) beam at Fermi Lab produces the muon neutrinos and anti-neutrinos from 120 GeV protons striking a graphite target producing positive and negative hadrons. MINOS deployed a far detector, 735m baseline at the Soudan mine in Minnesota, and a near detector, 1.04km from the neutrino source. The magnetized detectors are segmented steel and scintillator tracking calorimeters that detect μ^+ and μ^- particles from charge current interactions. The near detector provides an un-oscillated energy spectrum of the neutrino beam (figure 3.31), which is used to determine the expected spectrum at the far detector. For three run periods 1986 events were observed for 2451 un-oscillated event prediction. The distorted reconstructed energy spectrum at the far detector (figure 3.32) is used to calculate the oscillation parameters. The best fit values for oscillation parameters of the MINOS data are [39]:

$$\Delta m_{23}^2 = 2.32_{-0.08}^{+0.12} \times 10^{-3} eV^2$$

$$\sin^2(2\theta_{23}) > 0.90$$

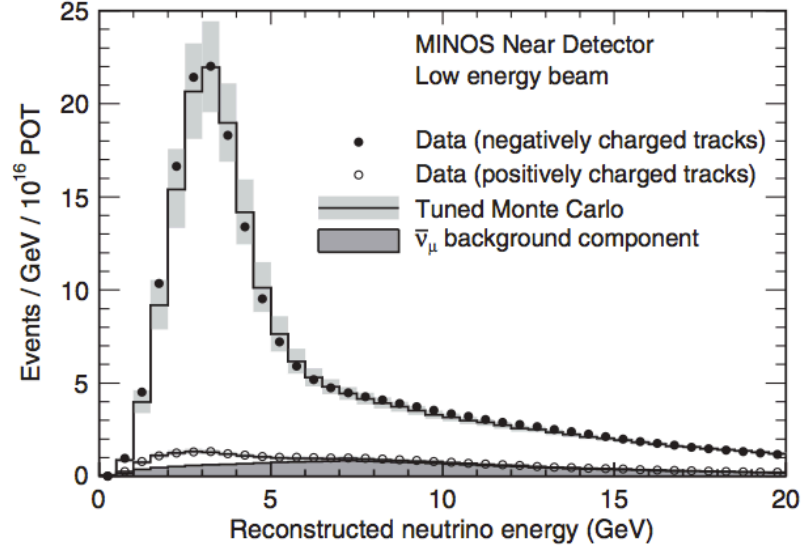


Figure 3.31: MINOS near detector reconstructed neutrino energy spectrum [39].

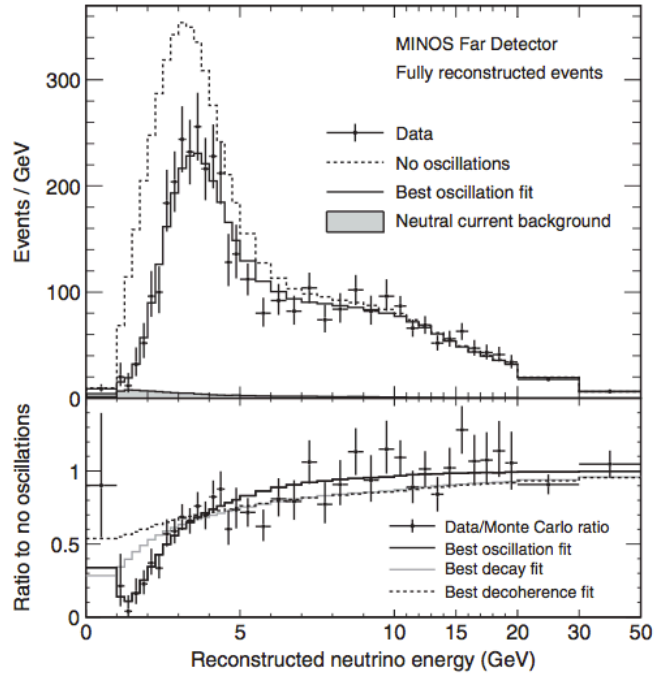


Figure 3.32: MINOS far detector reconstructed neutrino energy spectrum and ratio to no oscillation prediction [39].

Chapter 3.4.3 Atmospheric and Solar results

Compelling evidence for neutrino oscillations has been shown from solar, atmospheric, long baseline reactor, and accelerator neutrino experiments. The measurements of the neutrino mixing parameters θ_{12} and Δm^2_{12} were determined from solar experiments and KamLAND. For KamLAND the two-flavor approximation was used for reactor electron anti-neutrino survival probability.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx \cos^4 \theta_{13} \left(1 - \sin^2 2\theta_{12} \cdot \sin^2 \left[1.27 \Delta m^2_{21} \left(\frac{L}{E} \right) \right] \right) \quad (3.6)$$

For atmospheric and accelerator experiments θ_{23} and Δm^2_{23} were determined. Again the two-flavor approximation was used for the probability of muon neutrinos oscillating into tau neutrinos.

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \cos^4 \theta_{13} \sin^2 2\theta_{23} \cdot \sin^2 \left[1.27 \Delta m^2_{23} \left(\frac{L}{E} \right) \right] \quad (3.7)$$

Expanding to a three-flavor neutrino oscillation model both KamLAND and SK could obtain upper boundaries of θ_{13} . Neither experiment could exclude a zero value for θ_{13} (figure 3.33).

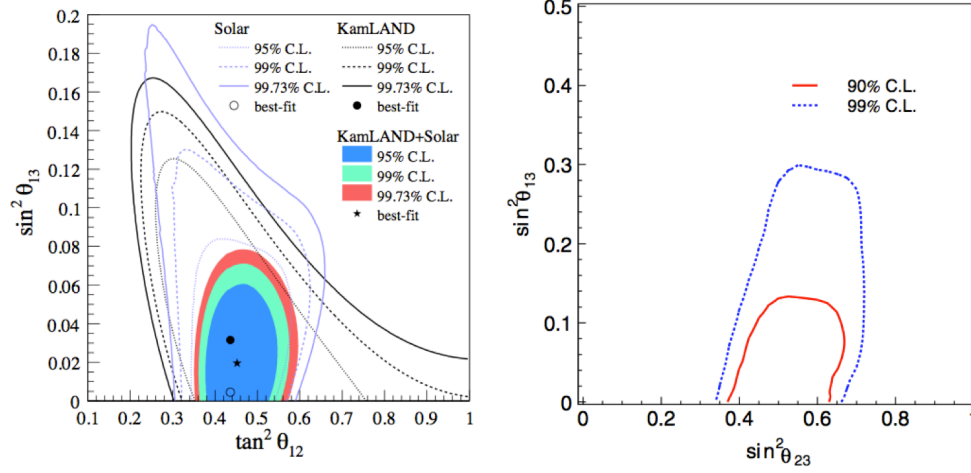


Figure 3.33: Contours of allowed region of θ_{13} for left-KamLAND [40] and right Super-Kamiokande (positive Δm^2_{23})[41].

Chapter 3.5

Reactor Experiments

3.5.1 Short-Baseline Reactor Experiments

Through the 1980's and early 1990's several reactor anti-neutrino detectors were built at baselines of less than 100m. Each experiment detected electron anti-neutrinos via inverse beta decay (IBD) charged current reactions. At ILL a detector [42] was located at 8.76m from a reactor core in Grenoble, France. At the reactor in Gosgen, Switzerland, detectors were placed at 37.9, 45.9 and 64.7m [43]. Two detectors were deployed at 18 and 25 m from the Rovno nuclear power plant in Ukraine [44]. At the two reactors in Krasnoyarsk, Russia a detectors were placed at 57m and 231m from the cores [45]. Two detectors at 18 and 24m were built at the Savannah River Site production reactor in South Carolina [46]. In Bugey, France three detectors were used at distances of 15, 40 and 95m from the reactor [47]. These short-baseline experiments were in close agreement with the

expected neutrino flux rates with no oscillation. The combined ratio of observed to expected rate was 0.976 ± 0.024 . Although no oscillations were discovered, the various measurements were important to the understanding of reactor models and neutrino production inside the reactor.

A recent reevaluation of the flux calculations increased the estimated electron anti-neutrino production inside the reactors. This meant that the combined ratio of data to expected flux was lowered to 0.943 ± 0.023 (figure 3.34) giving rise to what is known at the “reactor antineutrino anomaly” [48]. The possibility of an additional “sterile” neutrino flavor could explain this deviation. For this thesis a three-flavor neutrino model will be assumed.

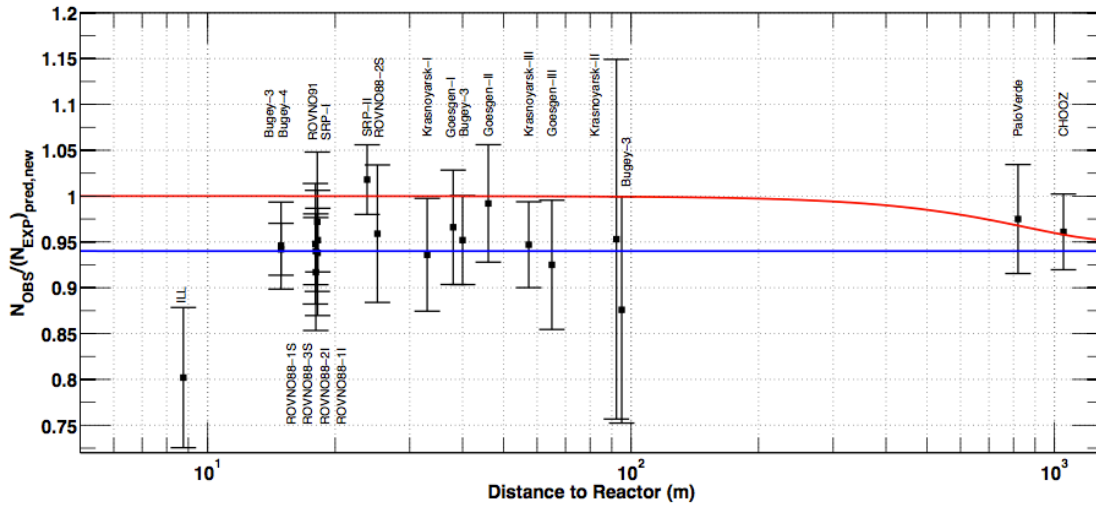


Figure 3.34: Short-baseline anti-neutrino experiment summary.
With updated electron anti-neutrino flux calculations [48].

Chapter 3.5.2 CHOOZ

The previous short-baseline reactor experiments did not observe oscillations due to the two-flavor oscillation probability.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2 \left[\frac{1.27 \cdot \Delta m_{32}^2 (eV^2) \cdot L(m)}{E_\nu (MeV)} \right] \quad (3.8)$$

For the value of the atmospheric mass splitting term ($2.4 \times 10^{-3} \text{ eV}^2$) and the energy spectrum of reactor anti-neutrinos ($\sim 3.5 \text{ MeV}$ peak) the distance to first maximum for oscillation is $\sim 1.1 \text{ km}$. The short baseline experiments ($< 100 \text{ m}$) were far short of the optimal distance for oscillations.

The CHOOZ experiment [49] was built 1.05 km from the Chooz-B nuclear power station. Located in the Adrennes region of northeastern France, there are two 4.25 GW_{th} twin pressurized-water reactors (PWR).

The CHOOZ lab was located underground with 300 (meters water equivalent) MWE of overburden to shield the detector from cosmic ray muons. To shield from natural radioactivity from the rock in the 7m deep pit, the detector was surrounded by 75cm of low radioactivity sand. The three volume detector, housed inside a 5.5m diameter and 5.5m deep steel vessel, consisted of an active muon veto shield, intermediate region, and central target region (figure 3.35). The muon veto shield was a 90-ton vessel of liquid scintillator with 48 eight-inch photomultiplier tubes (PMTs). Cosmic ray muons are tagged with this volume in order to reject background signals. The intermediate region was a 17-ton vessel was optically separated from the muon veto region and housed 192 eight-inch PMTs. Filled with liquid scintillator, the intermediate region was designed to protect the target area from radioactivity in the PMTs and contain gammas produced in the target. The inner target volume was an opaque plastic “geode” structure filled with 5-tons of Gadolinium (Gd)-loaded liquid scintillator. The Gd doped liquid scintillator increased the light output and decreased the capture time of the neutrons produced in the IBD interaction.

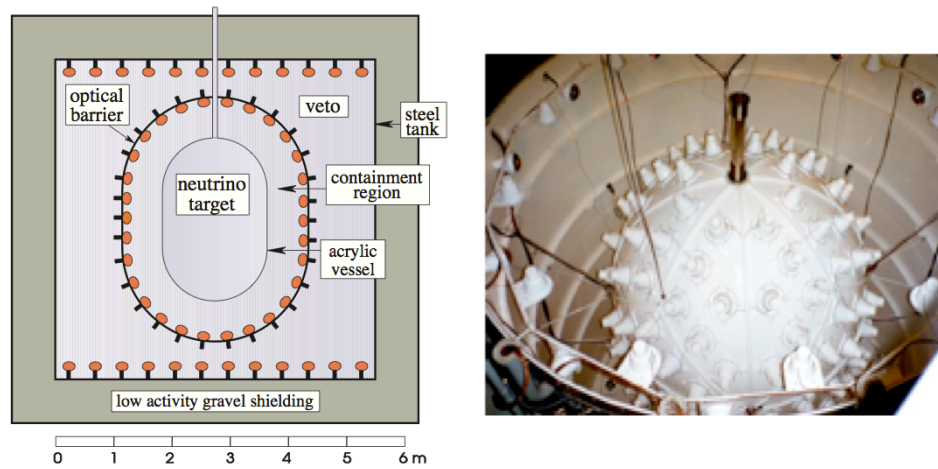


Figure 3.35: Left: Schematic of CHOOZ detector. Right: Picture of installed CHOOZ structures.

Table 3.2: Run-time summary of CHOOZ [49]

	Time (h)	$\int W dt$ (GWh)
Run	8761.7	
Live time	8209.3	
Dead time	552.4	
Reactor 1 only ON	2058.0	8295
Reactor 2 only ON	1187.8	4136
Reactors 1 & 2 ON	1543.1	8841
Reactors 1 & 2 OFF	3420.4	

342 days of live time was taken from March 1997 through July 1998 (Table 3.2). During the run time of CHOOZ the reactors were in final commissioning. The first reactor was not at full power until May 1997 and the second reactor until August 1997. Due to problems with the cooling system both reactors were taken off-line in February 1998. The data set included 41.6% with both reactors off and $\sim 39.5\%$ with only one reactor on. The data taking time with both reactors off allowed for a robust study of the backgrounds of the detector.

CHOOZ detected electron anti-neutrinos via the charged current inverse beta decay (IBD) interaction, same method as previous reactor neutrino experiments. Prompt,

positron annihilation, and delay signals, neutron capture on Gd, were used to identify IBD events. Using a loose cut of $\sim 4\text{MeV}$ on the delay event energy, the prompt/delay signal distribution shows the background and IBD candidate regions can be seen (figure 3.36).

A series of cuts were applied to remove backgrounds leaving a pure IBD sample of event. 1) The first cut is of positron energy $< 8\text{ MeV}$ is applied to limit the signal from only incoming electron anti-neutrinos. From reactor calculations the contribution from IBD events above 8MeV is $< 0.05\%$. 2) To limit the delay event to only neutron captures on Gd, a cut of $6\text{-}12\text{MeV}$ is used. 3) Fiducial volume cut of 30cm from the geode boundary was applied for both positron and neutron events. These cuts are to ensure that the candidates originate from within the target area. 4) The relative position between the prompt and delay events were cut to be less than 100cm . This position cut removes random candidates that might originate in different parts of the detector and is well above the expected neutron capture path length. 5) The time delay between prompt and delay event is limited to $2\text{-}100\mu\text{s}$. 6) The final cut is on neutron multiplicity above one. The summary of the selection efficiencies is given in table 3.3. With just the application of spatial and time cuts, 3-5, only 10% of background remains (figure 3.37).

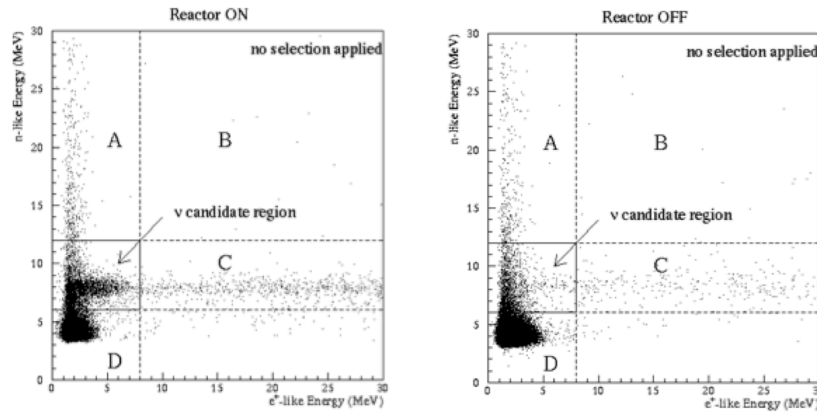


Figure 3.36: Neutron-like versus positron-like events for CHOOZ
left – reactor on data, right – reactor off data [49]

Table 3.3: Selection cut efficiencies and errors for CHOOZ [49].

selection	$\epsilon(\%)$	rel. error (%)
positron energy*	97.8	0.8
positron-geode distance	99.9	0.1
neutron capture	84.6	1.0
capture energy containment	94.6	0.4
neutron-geode distance	99.5	0.1
neutron delay	93.7	0.4
positron-neutron distance	98.4	0.3
neutron multiplicity*	97.4	0.5
combined*	69.8	1.5

*average values

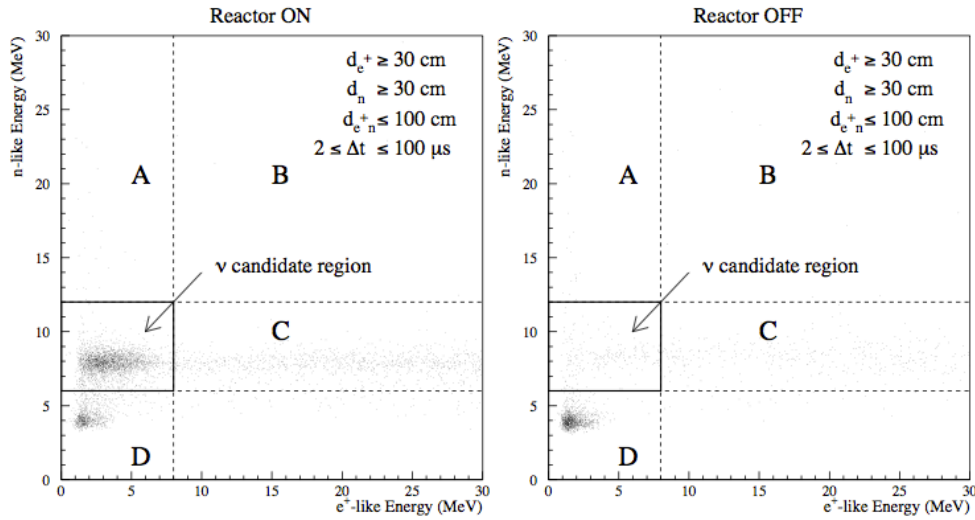


Figure 3.37: Neutron-like versus positron-like events after position and time cuts for CHOOZ
left – reactor on data, right – reactor off data [49]

After all cuts are applied the ratio of measured to expected neutrino rate at the CHOOZ detector was $1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$ (figure 3.38). The 2.7% systematic error for CHOOZ was dominated by the uncertainties in the reactor neutrino production (table 3.4). The statistical error, 2.8%, was driven by the limitation of run time available with the reactors on. During the year of data taking the photoelectron yield of the scintillator began to decrease due transparency degradation. When the reactors were shut

down in February of 1998, which was scheduled to last for over one year, it was clear that it was not feasible to continue running until the reactors were brought back online.

Table 3.4: Systematic error contributions for CHOOZ [49].

parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

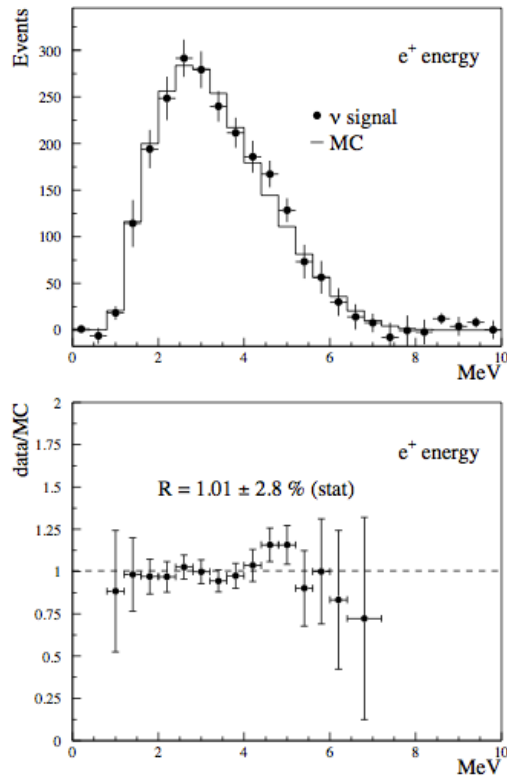


Figure 3.38: (above) Measured and expected positron spectrum from CHOOZ.
(below) Ratio of measured to expected ratio[49]

Chapter 3.5.3 Palo Verde

The Palo Verde Nuclear Generating Station in Arizona was the site of another reactor neutrino experiment. Three pressurized water nuclear reactors (11.63 GW_{th} total power) were the electron antineutrino source for a detector located 890 m from two reactors and 750 m from the third reactor. The data set of Palo Verde was accumulated from September 1998 to July 2000. The detector consisted of 66 acrylic cells filled with a total of 11.34 tons of Gd-loaded liquid scintillator. The cells are monitored by two PMTs separated from the liquid scintillator by buffer oil. The central detector was surrounded by 105 tons of water as shielding from outside radiation. A 4π active muon veto surrounds the water shielding (figure 3.39).

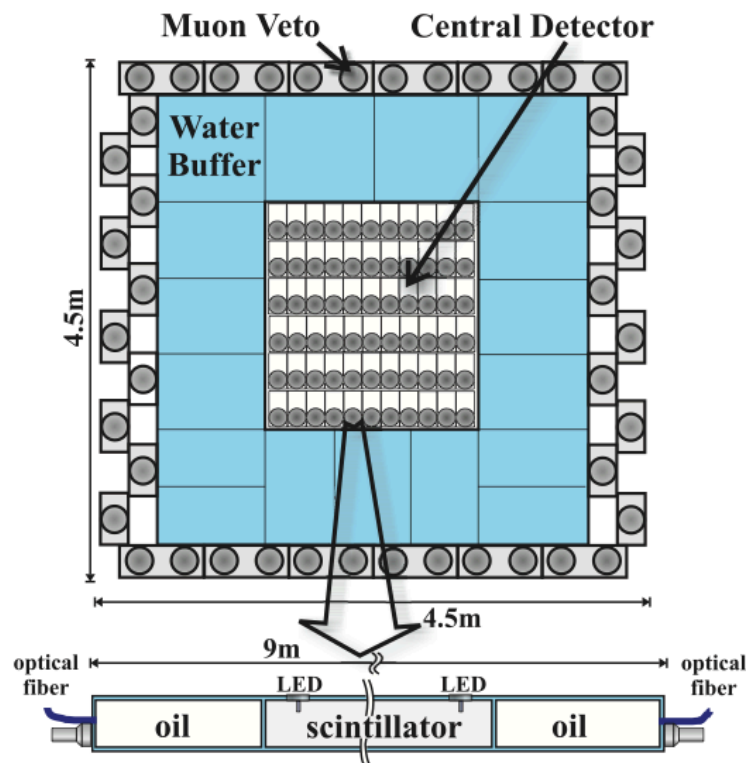


Figure 3.39: Schematic of the Palo Verde Detector [50]

As with other reactor experiments, electron antineutrinos are detected from inverse beta decay interactions. Similar to CHOOZ, Gd is used to decrease neutron capture time and increase light production from the capture. From the 350.5 days of data no evidence of electron antineutrino disappearance was found. The calculated rate to the expected rate was 1.011 ± 0.104 (figure 3.40). The limits for the θ_{13} parameter were similar to those determined from CHOOZ (figure 3.41) [50].

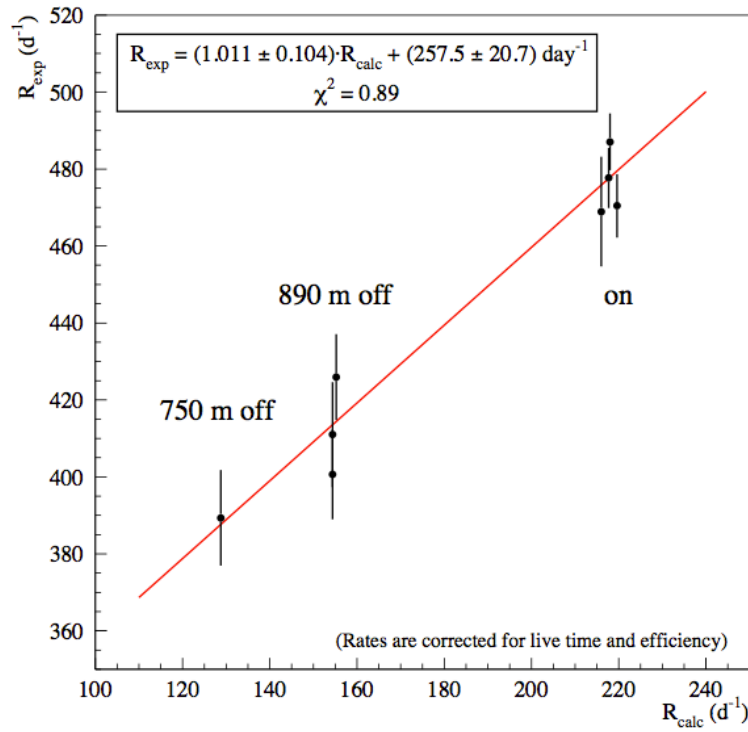


Figure 3.40: Rate expected versus calculated rate (plus background and dead time compensation) for Palo Verde [50]

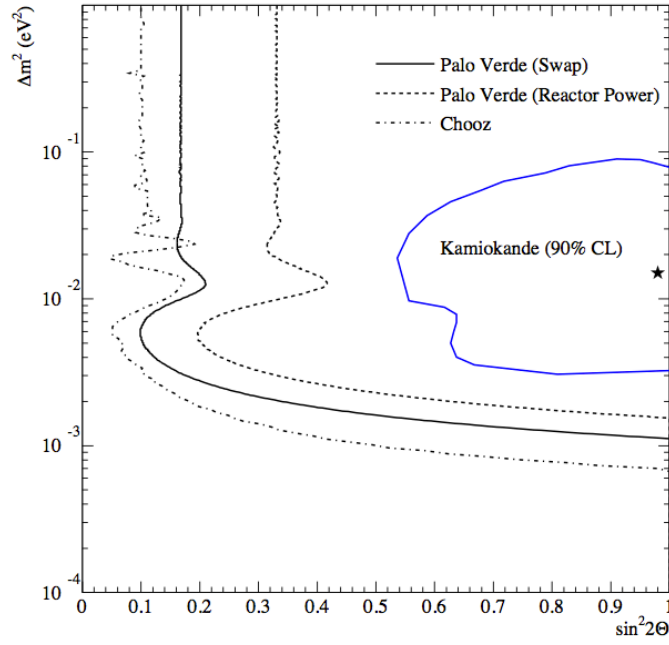


Figure 3.41: 90% CL exclusion curves for two-flavor oscillations from Palo Verde and CHOOZ. Kamiokande allowed region and best fit from atmospheric neutrino results for θ_{23} are also shown [50].

Chapter 4

Double Chooz Experiment

Chapter 4.1

Introduction

The Double Chooz (DC) experiment is a reactor neutrino experiment located in the Ardennes region of northern France. In order to probe the θ_{13} parameter of neutrino oscillation by measuring the survival of electron anti-neutrinos produced from the reactors at the Chooz-B Nuclear Power Station (figure 4.1). The original CHOOZ experiment (described in Chapter 3.5) was able to put the lowest bound on the oscillation parameter θ_{13} . Double Chooz utilizes the original CHOOZ lab located 1.05km and 0.998km from the west and east reactors at Chooz-B. This “far” detector measures the oscillated flux of electron anti-neutrinos based on a nonzero value of θ_{13} . To address the largest systematic uncertainty of CHOOZ, the neutrino flux from the reactors, a second identical “near” detector will be deployed. The near detector, located ~ 400 m from the reactors, will measure the unoscillated neutrino flux. With the measured unoscillated flux the uncertainties arising from the limited knowledge of neutrino production are negligible. Building identical detectors also reduces detector systematic uncertainties. The two detector concept will bring down the systematic uncertainty to 0.6% for Double Chooz. This is an improvement from CHOOZ systematic uncertainty of 2.7% [51]. Phase-I of Double Chooz is with only the far detector running as the near detector is constructed and improvements.



Figure 4.1: Chooz-B nuclear reactor site in northeastern France. Near Lab (~400 from reactor cores) and Far Lab (~1.05km from reactor cores) are shown.

Many improvements in the detector design were made from CHOOZ to Double Chooz. Double Chooz detectors include three inner regions; target volume, gamma catcher, and buffer regions. The addition of the gamma catcher region will eliminate a need for any fiducial cuts by containing gammas from reactions within the target. The target volume of Double Chooz detector is 10.2 m^2 , which is nearly double the size of the CHOOZ detector. Degradation of the liquid scintillator limited the statistics taken for the CHOOZ experiment (described in Chapter 3.5). Improvements were made to both the chemistry and the handling of target liquid scintillator of Double Chooz. This chapter will detail the detector design.

Chapter 4.2

Detector Design

The DC detector is a multi-tiered detector consisting of an Outer Muon Veto (OV), Steel Shielding, Inner Muon Veto, and three-region inner detector (Figure 4.2).

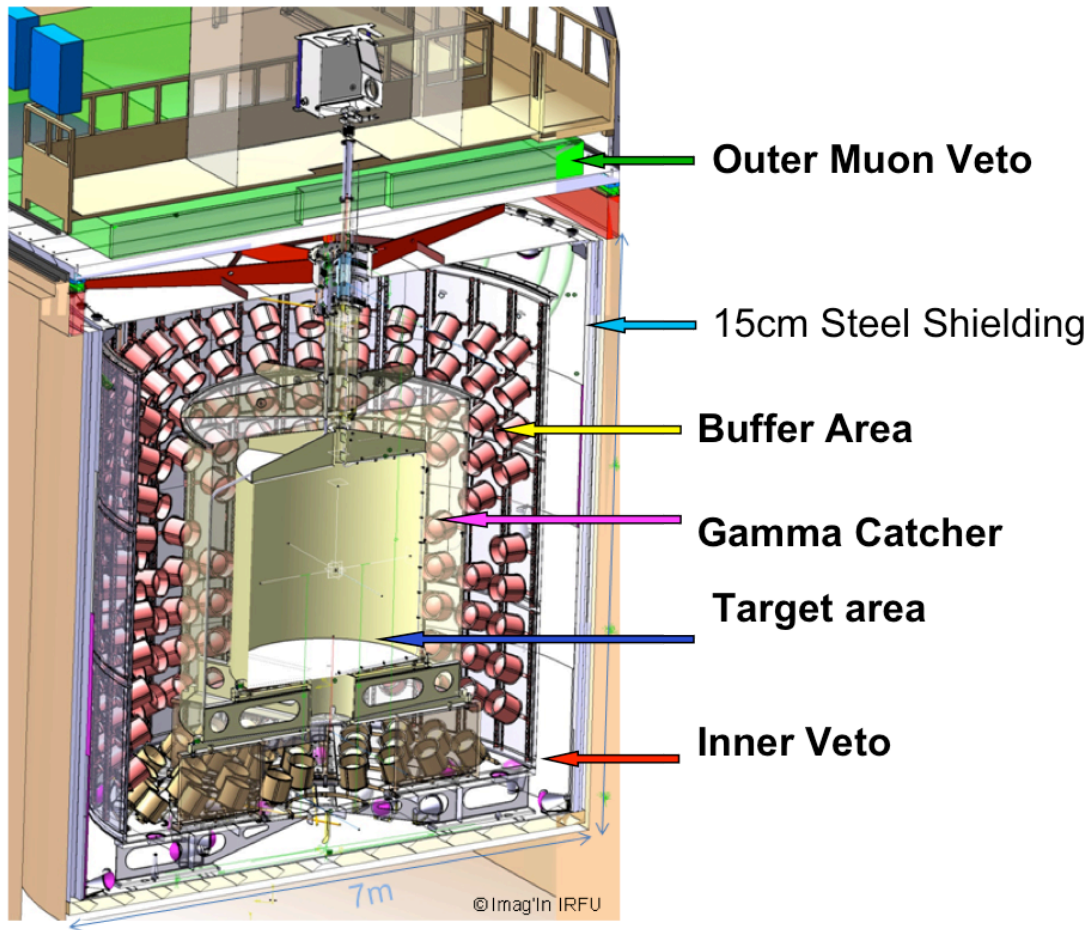


Figure 4.2: Diagram of Double Chooz Detector.

4.2.1 Outer Muon Veto

The purpose of the OV is tagging muons both entering the detector and traveling outside the detector. The tracking capabilities of the OV will improve the efficiency of tagging muons entering the detector and provide spatial information beyond the capabilities of the Inner Muon Veto system. Muons traveling just outside of the detector volumes can also be tagged, which will assist in determination and subtraction of correlated backgrounds [51]. The OV consists of 36 “lower” modules arranged on the floor of the lab above the detector and 8 “upper” modules located at the top of the lab 5m above the floor modules. The upper and lower OV sections consist of two layers of

overlapping modules (figure 4.3) [52]. Each module is 1.623m x 3.625m consisting of plastic scintillator with wave shifting fibers (WLS) inserted through bore holes along the length of the plastic. The WLS fibers of the panels are read out by a multi-anode PMT. Muon hits are defined by simultaneous hits in X-Y panel pairs. The OV was not fully commissioned and OV data is not included in the first publication data set analysed for this thesis.

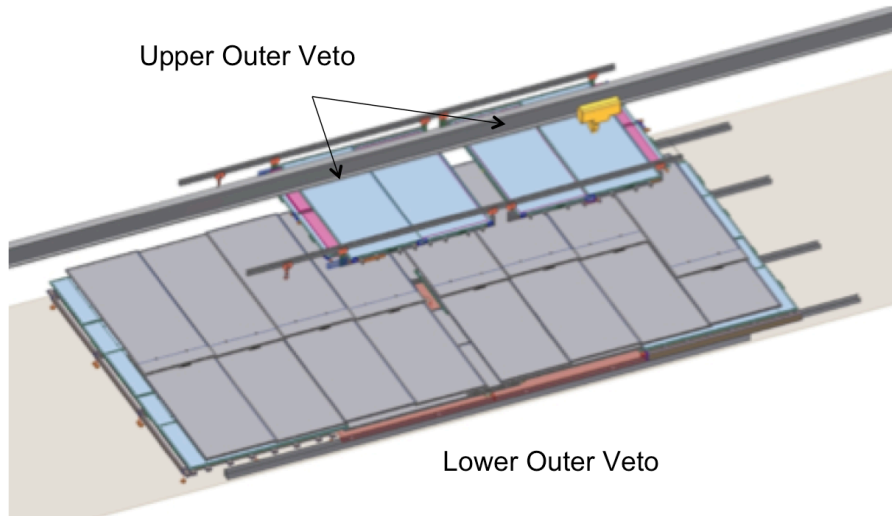


Figure 4.3: Schematic of upper and lower OV modules [52].



Figure 4.4: Installed lower OV panels.

4.2.2 Shielding

In order to minimize the impact of gamma-rays originating from the rock surrounding the DC detector, a 15cm steel shielding insert was installed. From studies performed by the CHOOZ experiment, the major contribution of the gamma-ray background originated from K, U and Th decay chains. The steel shielding provides higher suppression than the low radio-active sand used in CHOOZ (figure 4.5). To minimize any impact to PMT operation, the individual bars making up the steel shield were demagnetized prior to installation.

4.2.3 Inner Muon Veto

Muons passing into and near the detector are a major source of background for Double Chooz. The active inner veto allows for tagging of muons that enter the detector and, to a lesser extent, neutrons from muons just outside the detector. 4π coverage is

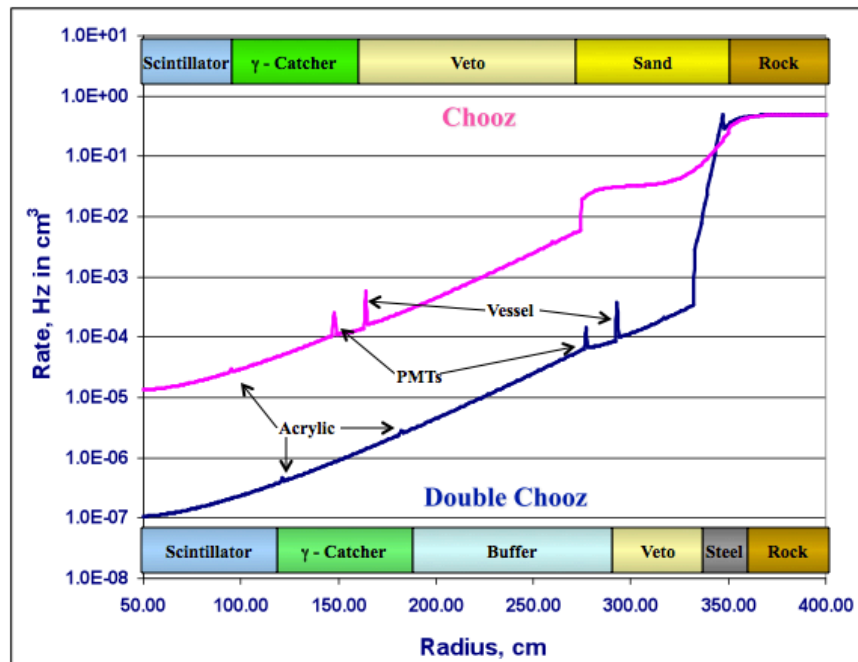


Figure 4.5: Comparison of predicted singles rates of CHOOZ and Double Chooz [51].

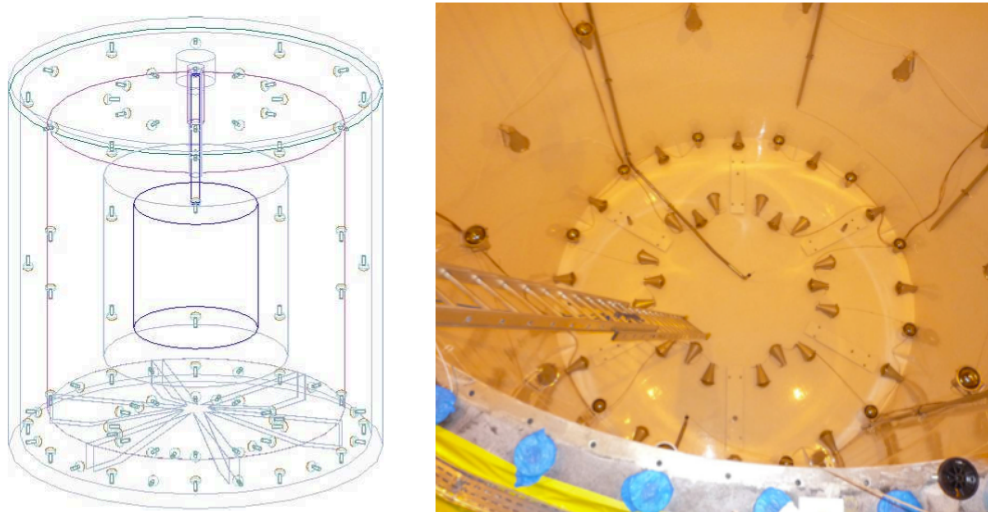


Figure 4.6: Left - Schematic of Inner Veto with PMT positions [51]. Right -Inner Veto vessel installed.

provided by the, 6.5m diameter 6.83m high, cylindrical vessel located inside the steel shielding. The vessel houses 78 eight-inch PMTs and is filled with 90m^3 of liquid scintillator (figure 4.6). The PMTs provide 0.6% coverage so to increase light yield, the surfaces of the vessel (sides, floor and lid) covered in reflective paint. The buffer vessel inside of the veto is lined with reflective VM2000 foil.

4.2.4 Buffer Vessel

Of the materials that the detector used to constructed the DC detector the glass of the photomultiplier tubes (PMT) introduces the highest rate of radioactivity into the detector. A 105cm buffer region, filled with 114 m^3 of non-scintillating oil, is used to lessen the impact on the singles rate. Such a buffer region, which was not utilized in the original CHOOZ detector, is a major design improvement of the DC detector. The buffer vessel is a cylinder (5.522m diameter and 5.68m height) made of 3mm thick stainless steel (figure 4.7). 390 PMTs inside magnetic shielding mounted on the walls, floor (shown in figure 4.7) and lid of the buffer provide $\sim 13\%$ optical coverage of the target region.

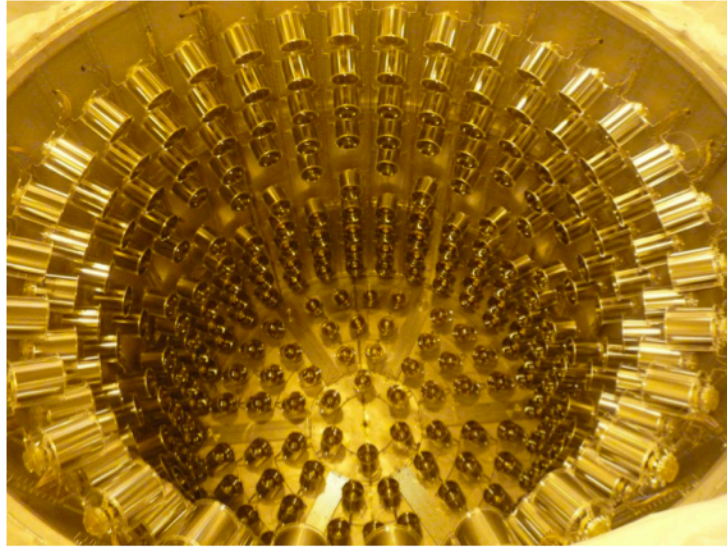


Figure 4.7: Double Chooz buffer vessel with side and floor PMTs.

4.2.5 Gamma Catcher and Target Acrylics

Two nested volumes, gamma catcher (GC) and target, made of transparent acrylic plastic are at the center of the DC detector (figure 4.8). The advantage of two scintillating regions is the containment of gamma rays produced near the edge of the neutrino target. This eliminates the need for a fiducial volume cut as used in CHOOZ reducing the uncertainty of the target protons. Considerations in the design of the acrylic vessels included physical strength, low radioactivity, optically transparent, and chemical compatibility to the scintillator. The acrylics are transparent to photons above 400nm to allow scintillation light to freely propagate to the PMTs. The vessels need to be stable for 5 years of DC operation. The acrylics were tested for compatibility with the target and GC scintillator liquids as well as the buffer oil. The gamma catcher is an acrylic cylinder (3.392 m diameter and 3.574 m height) that holds 22.3 m³ of liquid scintillator. The gamma catcher acrylics are 12 mm thick with a distance of 55 cm to the central target. The target vessel is a 5 mm thick acrylic vessel (2.30 m diameter and 2.458 m height), which houses 10.3 m³ of Gd-doped scintillator liquid.

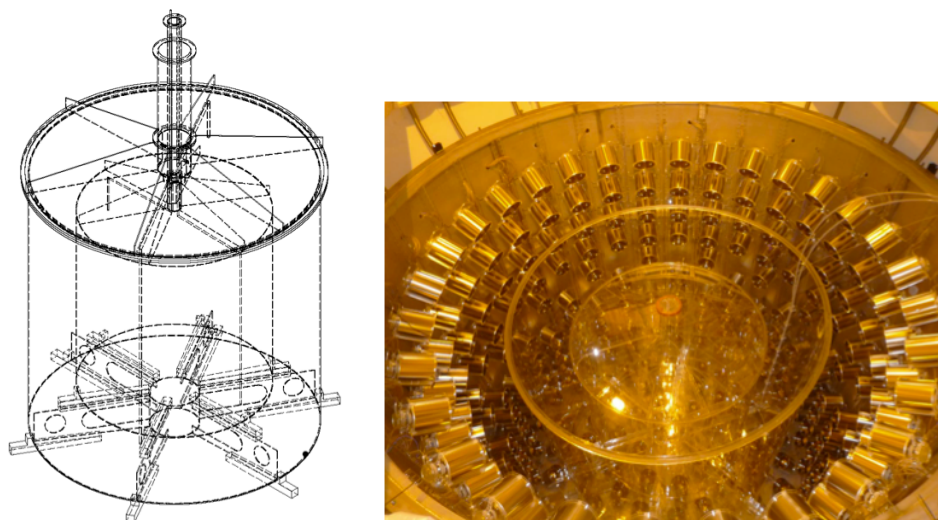


Figure 4.8: Left – Engineering model of acrylic vessels [51]. Right –Gamma Catcher and Target installed.

Chapter 4.3

Scintillator

The organic liquid scintillator converts energy lost by charged particles into light that is visible to photomultiplier tubes. In the scintillator aromatic components absorb energy resulting in excited molecules. The excited molecules are de-excited emitting photons. The primary fluorescence emission happens on a time scale of a few nanoseconds. To a lesser extent, phosphorescence can occur on a longer time scale up to μ seconds. The absorption and emission spectrum of the aromatic compounds are similar so additional wave-shifting fluors are needed. Fluors were chosen such that there is little overlap between the absorption and emission spectrums, called the Stokes Shift. Another role of the wave-shifters is to convert the emitted photons to the region of sensitivity of the photomultiplier tubes [53].

For Double Chooz special considerations were taken into account due to the three vessel inner detector design. Due to the fragility of the acrylic vessels, the densities of the three fluids (target, gamma catcher, and buffer oil) had to match within 1%. The index of refraction of the liquids required matching the index of refraction of the PMT

glass for optimal photon collection. The light yield between the target and gamma catcher was also required to be equal for proper energy resolution. Each of these goals was met for the final scintillator compositions (table 4.1).

The target scintillator liquid base is n-dodecane base (80%). N-dodecane was chosen to maximize the number of hydrogen atoms in the target. The aromatic compound added is Phenyl-o-Xylylethan, o-PXE, (%20). Two wave-shifting fluors are also included; PPO (7 g/L) and bis-MSB (20 mg/L). The molar extinction coefficients (absorption range) and emission spectrums of the components are shown in figure 4.9. Gd is also added to the target scintillator in the form of a Gd-beta-diketonate ($\text{Gd}(\text{thd})_3$) molecule. The beta-diketonate molecule allows for longer-term stability than molecules used in past experiments such as CHOOZ. For uniform energy resolution, the attenuation length in the target for light at 430nm needs to be large enough for light to propagate the length of the target. The target liquid attenuation length is 7.8 ± 0.5 m (at 430nm).

The gamma catcher scintillator is composed of 66% mineral oil (Ondina909), 30% n-Dodecane, 4% PXE, 2 g/L PPO, and 20 mg/L bis-MSB. The addition of Ondina mineral oil was to increase the transport of light and match the density of the target liquids. The concentrations of PPO and PXE were lowered from optimal levels so that the light yield would remain constant between target and gamma catcher [54].

The buffer liquid is composed of non-scintillating oils (47.2% Corbersol C730 and 52.8% Ondina917). The buffer oils serve to absorb gamma radiation from PMTs before reaching the active volumes and allow light produced in the target and gamma catcher to propagate to the PMTs.

Table 4.1: Properties of the DC target and gamma catcher scintillator [54].

	Target	Gamma Catcher
Density [kg/l] at 15°	0.8035 ± 0.0010	0.8041 ± 0.0010
kinematic viscosity [mm ² /s] at 21°	2.32 ± 0.10	3.70 ± 0.10
Water content [ppm]	36 ± 1	9 ± 2
attenuation length at 430 nm [m]	7.8 ± 0.5	13.5 ± 1.0
Light yield [% BC-505]	48.1 ± 0.5	46.6 ± 1.0
Potassium [ppb]	< 2	< 2
Refractive index at 405 nm (18°)	1.47	1.46
Gd-concentration [wt.%]	0.123 ± 0.002	–
Hydrogen fraction [wt.%]	13.60 ± 0.04 (calculated)	14.6 ± 0.2 (measured)

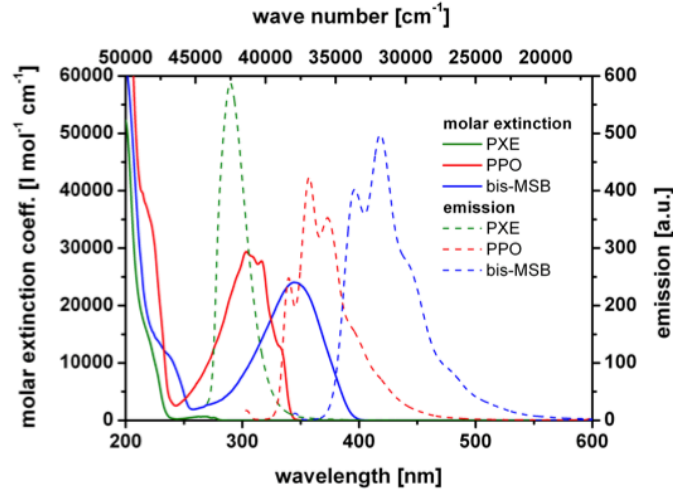


Figure 4.9: Molar extinction coefficients and emission spectrum for DC liquid scintillator components [55].

Chapter 4.4

Photomultiplier Tubes

For the detection of light produced by the scintillator liquids, 468 PMTs (390 inner detector and 78 inner veto) were installed in the Double Chooz detector. PMTs operate on the photoelectric effect concepts. The glass window of PMT has a thin film of low work function material called the photocathode where incident photons eject

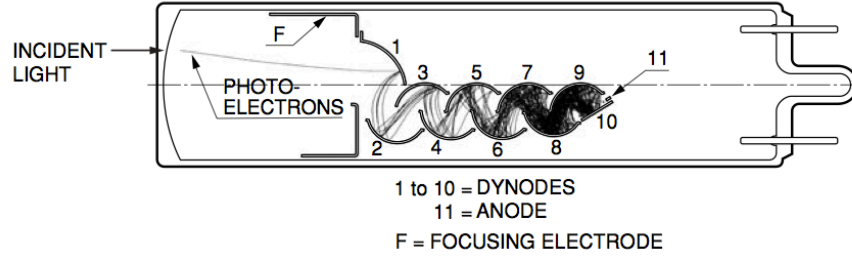


Figure 4.10: Schematic of electron multiplication of a PMT[56].

electrons. The quantum efficiency (QE) of a PMT is the probability that a photon will produce a photoelectron. The photoelectrons are accelerated to a series of dynodes that eject multiple electrons for every incident electron. A high voltage power supply is used to apply electric potentials between the dynodes to accelerate the electrons. The number electrons resulting from a single photoelectron is called the gain of a PMT. The electrons are collected on an anode, which produces a measureable pulse (figure 4.10) [56].

The high voltage (HV) to the DC PMTs is supplied by a CAEN SY1527LC HV crate with A1535P HV modules. The modules have 24 positive HV channels with typical voltages between 1300 and 1800 V. All PMTs have a single cable, which carries HV and signal. The single cable arrangement limits the materials used inside the detector and allows for signal noise reduction. The PMT signal is decoupled from the HV in the PMT cable with a custom splitter circuit and sent to the front-end electronics for processing (figure 4.11) [57].

4.4.1 Inner Veto PMTs

The 78 PMTs used for the inner veto are 8-inch Hamamatsu R1408 that were previously used for the IMB experiment [59]. The R1408 PMTs have a bi-alkali photocathode that has sensitivity to photons between 300-650 nm. A venetian blind dynode structure is used to multiply the electrons [56]. To isolate the electronic

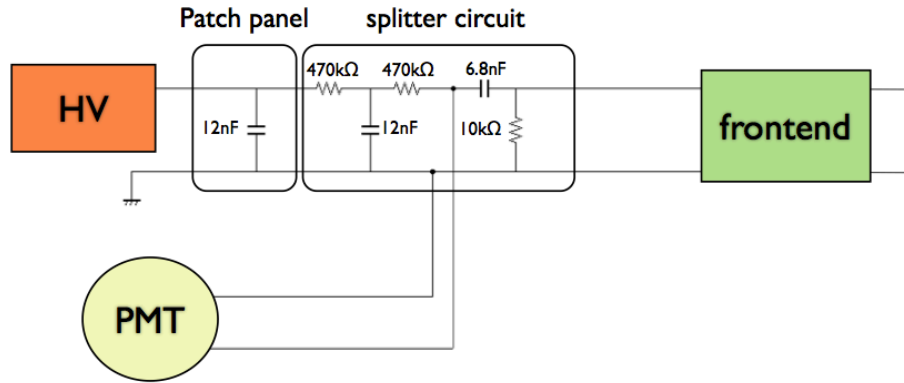


Figure 4.11: Splitter Circuit and interface between HV, PMT and front-end electronics [58].

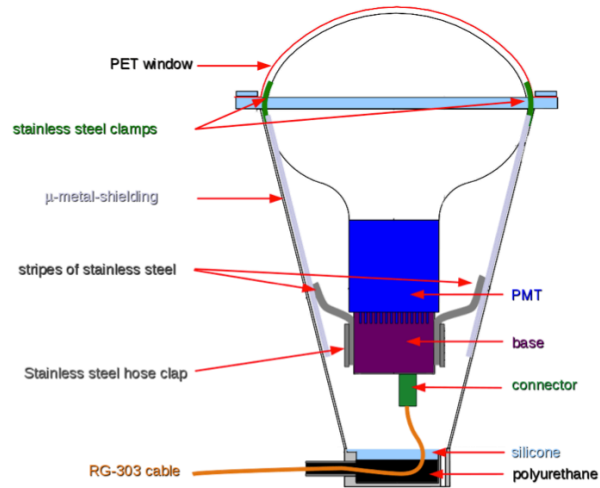


Figure 4.12: Schematic of the inner veto PMT encapsulations [60].

components of the PMTs they were encapsulated inside a stainless steel body (figure 4.12). A magnetic shielding was included in the encapsulation to reduce the impact of magnetic fields within the dynode structure. The PMT cable was potted in polyurethane and silicone to seal the encapsulation and remove any stress on the cable connection to the PMT base. To allow photon collection a PET window, secured by a metal flange, covers the PMT photocathode. The encapsulation is filled with mineral oil and is isolated from the scintillator of the inner veto.

4.4.2 Inner Detector PMTs

The inner detector PMT system consists of 390 10-inch Hamamatsu PMTs R7081. The specifications for the PMTs are given in table 4.2. The bialkali photocathode has sensitivity to 300-650nm photons. A platinum coating glass furnace was used to form the PMT glass to reduced the radioactive contaminates. 800 PMTs were produced and split between institutions in Japan and Germany for quality testing. Acceptable values for dark rate, single photoelectron resolution, transit time, and quantum efficiency (QE) were part of the qualification tests performed in Japan and Germany [61,62]. The large area PMTs are highly affected by external magnetic fields due to the long trajectories of the photo electrons. To reduce this affect and maintain proper resolution magnetic shielding was implemented into the PMT support structure [63]. Selected PMTs and magnetic shields were assembled with low radioactive, transparent acrylics for attachment in the buffer vessel (figure 4.13).

The energy resolution for the inner detector of Double Chooz was expected to be $7.5\% / \sqrt{E(\text{MeV})}$ with the output of the target scintillator being 6500 photons/MeV [51]. With an average QE of $\sim 23\%$ and 13% optical coverage, the photoelectron (p.e.) yield will be ~ 180 p.e./MeV. The photons will be spread isotropic about the detector meaning individual PMTs, for events below ~ 2 MeV, will typically only detect single photons. The inner detector PMT must have strong resolution to single photoelectrons (figure 4.14). The single photoelectron gain was determined for individual PMTs and used for proper energy reconstruction.

Table 4.2: Specifications of DC inner detector PMTs [62].

General parameters of R7081	Description
Spectral Response	300 to 600 nm
Peak Wavelength	420 nm
Material of photocathode	Bialkali
Effective photocathode area	220 mm dia.
Structure of dynodes	Box and Line
Number of dynodes	10
Storage Temperature	0 to +40 (°C)

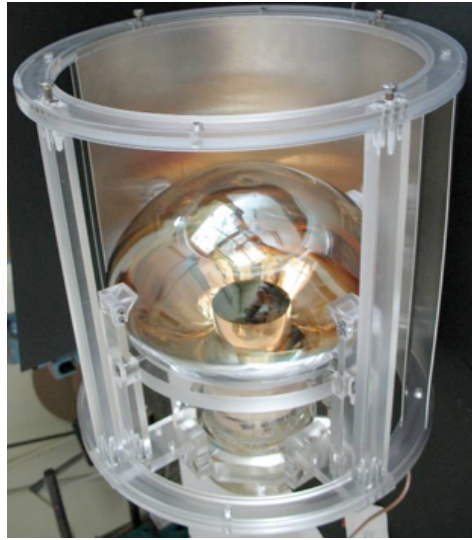


Figure 4.13: Inner detector PMT assembly (only half of the magnetic shield is present for demonstration) [64].

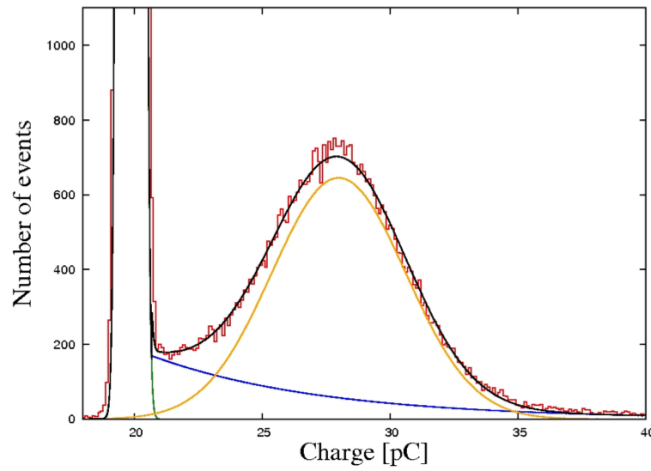


Figure 4.14: Single photoelectron charge spectrum of DC Inner Detector PMT [61].

Chapter 4.5

Data Acquisition System

4.5.1 Front-End Electronics

The PMT signals from the splitter boxes travel along 24 m to the custom built Front-End Electronics (FEE). The functions of the FEE include amplification of the PMTs (for both neutrino and muon channels), noise filtering, baseline restoration, and analog summation of pulses for the trigger electronics. Eight PMT inputs are available in each of the FEE modules built in NIM standard . Since typical PMTs signals are on the order of 5mV, which is too small for digitization, the raw signals were amplified by a factor of 7.8. The amplification occurs in steps along a chain of components (figure 4.15). Outputs of the neutrino channels go to the waveform digitizer and eight to one sum components. Muon interactions deposit large amounts of energy in the detector. To handle these large signals a muon channel provides an amplification of 0.5.

The trigger system is not designed to handle all PMT signals individually. The FEE combines the signals into 16 PMT channel blocks. The FEE modules sum 8 channels into 1 output (figure 4.16). The summed outputs of two modules are combined and reshaped through integration and differentiation (figure 4.17). The result is a wider pulse in which the scaled amplitude is proportional to the total summed charge (figure 4.18) [65].

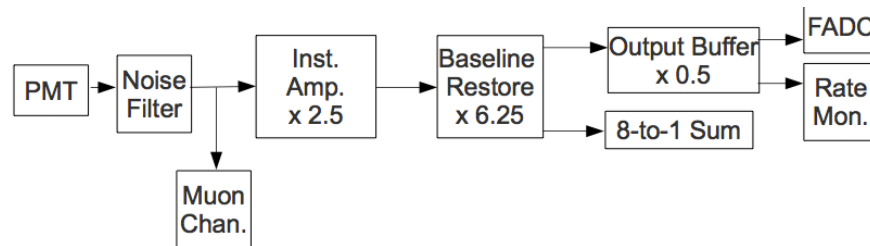


Figure 4.15: Block diagram of neutrino amplification channel of DC FEE [65].

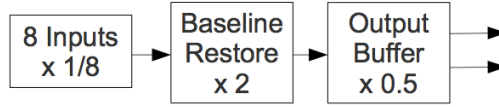


Figure 4.16: Block diagram of 8:1 summation channel of DC FEE [65].



Figure 4.17: Block diagram of module summation and pulse stretcher of DC FEE [65].

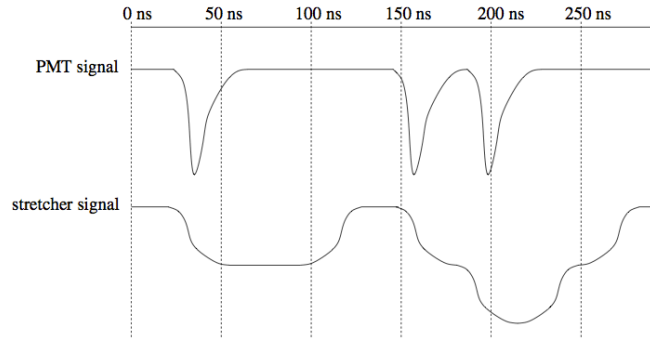


Figure 4.18: Scheme of stretcher pulse from FEE to the trigger boards [66].

4.5.2 Trigger System

For Double Chooz a two level trigger system is used for the data acquisition system. The level-I trigger system is the hardware trigger and level-II trigger is software “data reducer”. The level-II system is a set of fast analysis algorithms that allows the rejection of data deemed irrelevant to neutrino analysis. This vastly decreases the data storage and transfer requirements [51]. Currently only the level-I trigger has been implemented for the DC far detector.

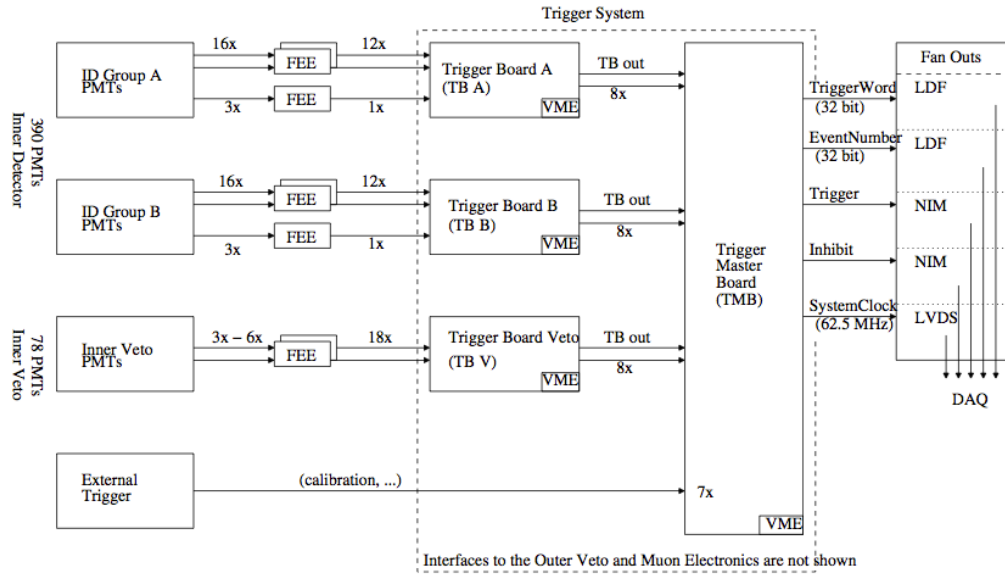


Figure 4.19: Scheme of Trigger Boards Interface [67].

The level-I (hardware) uses several levels of discrimination and logic to decide what digitized information is stored for analysis. The trigger consists of three detector trigger boards and one master trigger board all of which are custom built VME standard modules. Two of detector trigger boards (TB-A and TB-B) are for the inner detector PMT signals and the third (TB-V) is for the inner veto PMT signals. Logic units in TB-A, TB-B, and TB-V send discriminated conditions to the trigger master board (figure 4.19).

The two inner detector trigger boards contain an equal number of PMTs that are evenly distributed around the detector. Both TB-A and TB-B observe the same detector volume. This provides a tool for trigger efficiency determination and a crosscheck of trigger stability.

The trigger boards receive up to 18 analog inputs from the 16 channel summed pulse of the FEE. These 16 channel summed pulses are discriminated at various levels to provide the trigger conditions to the trigger master board. The individual sum inputs are discriminated at two levels to determine multiplicity conditions of a possible trigger. In

each trigger board all the input channels are summed and sent to four separate discrimination levels. The four levels of discrimination are pre-scaled, low (positron like), high (neutron like), and very high (muon like) (figure 4.20). The pre-scaled threshold is set at 0.2 MeV and is used for trigger efficiency determinations. The rate of events at this low threshold is much too high so only a scaled number of these events are triggered. The low-threshold is for positron-like events and is at 0.5 MeV, which is well below the minimum energy for positrons. The high-threshold is 5 MeV and is for the range of neutron capture on Gd. The threshold and multiplicity conditions that are met in TB-A and TB-B are passed along to the trigger master board.

Similar threshold decisions are set in the inner veto trigger board (TB-V). The sum of all 78 IV PMTs has two main threshold levels. The first threshold is set at > 250 photoelectrons for neutron-like events and the second is > 3000 photoelectrons for muon-like events. As with TB-A and TB-B, the trigger conditions are passed on to the trigger master board.

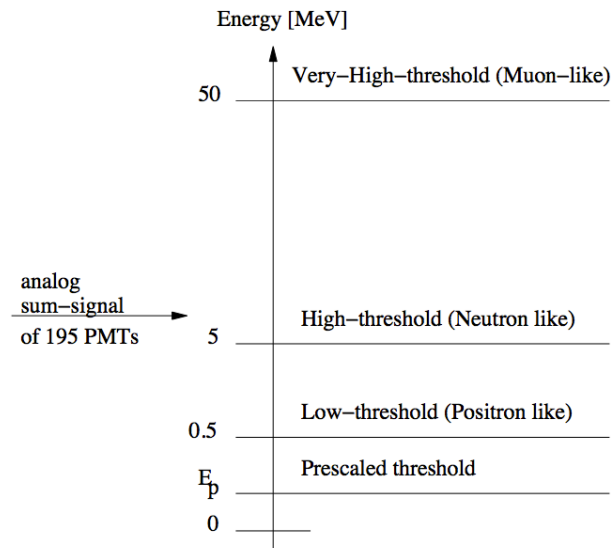


Figure 4.20: Threshold levels for inner detector trigger boards [67].

6Along with the detector trigger board inputs, the trigger master board (TMB) receives inputs from external trigger sources. These external triggers include: ID LED (for light injection calibration), IV LED (for light injection calibration), radioactive-tagged source, laser 470 nm, laser 365 nm, dead time monitor, and outer veto. If any of the trigger conditions are met, the TMB sends a signal to the FADC cards to read out the event. The TMB provides a 65.5 MHz clock to the entire DAQ system to ensure synchronization. The final function of the TMB is to write a “trigger word” to the data, which contains information about the trigger conditions [67].

4.5.3 Flash-ADC

The goal of the Double Chooz DAQ was to record digital waveforms for all 468 PMT channels for events above 0.5 MeV in the Inner detector and 5 MeV in the Inner Veto. The advantage of the digitization of the waveforms is the flexibility in charge reconstruction [51]. To record waveforms, without the introduction of hardware deadtime, custom 8-bit Flash-ADCs are utilized. The FADC cards were co-developed by AstroParticle and Cosmology Laboratory (APC) and Construzioni Apparecchiature Elettroniche Nucleari (CAEN). Each card has 8 channels of input sampling at 500MHz (2ns time resolution) to precisely record the pulse shapes. There are 256 ADC counts for amplitude resolution, where a single photoelectron is roughly 8 ADC count amplitude (figure 4.21) [68]

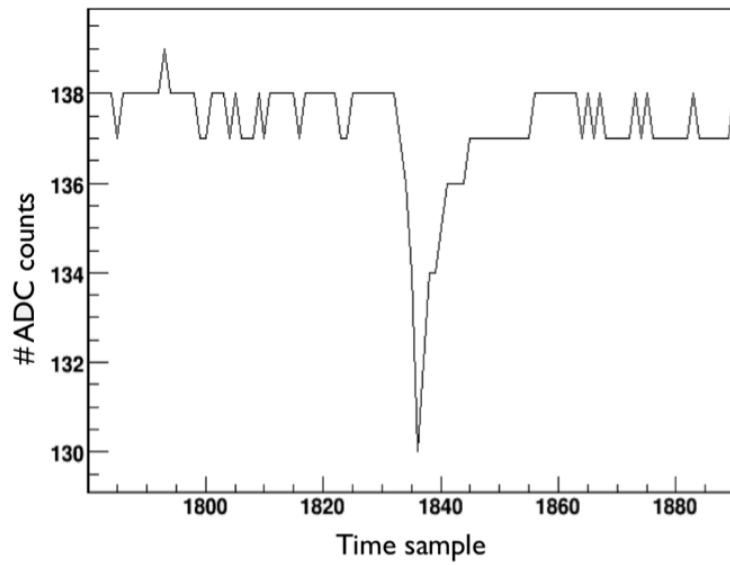


Figure 4.21: Digitized single photoelectron pulse [68].

Each FADC channel has 2 MBs of memory split into 1024 pages on a rotating buffer (figure 4.22). The digitization is continuously written; once the end of the page is reached the data is overwritten until a trigger signal is received. If a trigger is received the page is advanced and writing continues. The triggered page is marked as the readout index until the VMEbus can transfer the data. Dead time will occur if the readout indexed page reached the write index page [68]. In the current DC configuration, the readout window is 256ns with pulses start times ~ 100 ns into the readout window.

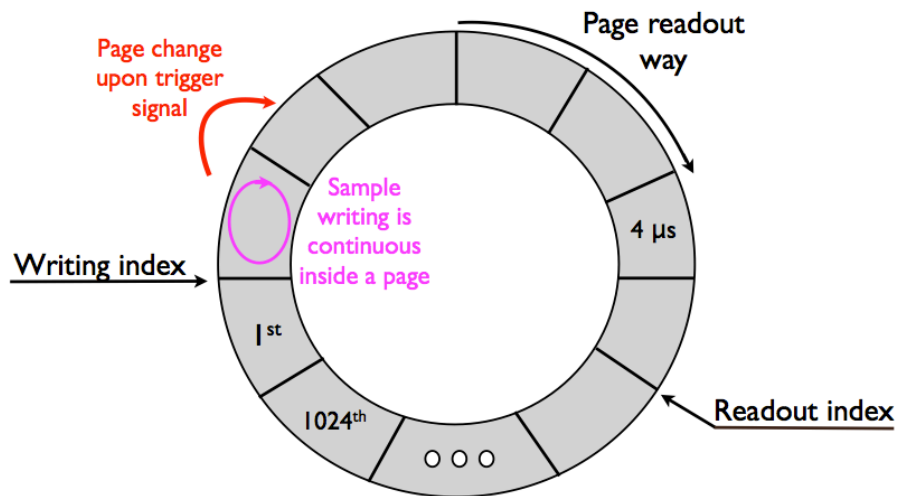


Figure 4.22: Illustration of memory allocation for channels of the FADC [68].

Chapter 4.6

Data Reconstruction Software

The Double Chooz Offline Group Software (DOGS) is the framework for both the Monte Carlo (MC) and data reconstruction. The first step in the chain of data handling occurs by the “DOGSification” process. The raw binary data is converted into ROOT (a C++ based data analysis framework) format with waveform information for individual channels as well as global information (trigger time, event number, trigger word, etc.) for every event. The data is then passed through the “common trunk” (CT) set of reconstruction algorithms. RecoPulse is the CT analysis framework that calculates the charge, timing, and pedestal for every channel of every recorded event. The pedestal (signal with no pulse present) is calculated in two ways and used to calculate the charge collected and quality of data. The first method is from waveforms recorded from external triggers. The external triggered waveforms should be absent of pulses with the exception of occasional dark rate signals. The second pedestal calculation come from the first few samples of the waveform before the pulse which starts $\sim 100\text{ns}$ into the readout window. The second approach takes into account any baseline shifts that can occur following large pulses like those from muon events. The threshold for pulse analysis comes from equation 4.1:

$$Q_{\min} = n_{\sigma} * \sigma_{\text{ped}} * \sqrt{(WS)} \quad (4.1)$$

Where σ_{ped} is the RMS of the pedestal, n_{σ} is the number of σ_{ped} for the threshold level, and WS is the time window for analysis. Once the threshold conditions are met a sliding 100ns window is used for integration of the pulse [69]. The charge collected values and timing information are recorded along with pedestal information.

RecoBAMA is a CT position reconstruction algorithm used to determine the spatial information of recorded events. Event start-time and charge distributions are used to determine the center of the reconstructed event.

Chapter 4.7

Detector Simulation Software

The DOGS (Double Chooz Offline Group Software) software package is used in the Monte Carlo (MC) simulations for Double Chooz. The DOGS MC is a Geant4 base with inputs and modifications specific to the Double Chooz detector. Based on inputs of the detector geometry, materials, and optical properties the DCGLG4sim calculates the number of photoelectrons detected by the PMTs for particle interactions. The ROSS (Read-Out System Simulation) package is then used to simulate the electronic component (PMT, FEE, FADC, and Trigger) response of events. ROSS outputs MC data in the same format as real data. This MC data is processed with the CT as described in the previous chapter.

Chapter 4.8

Calibration System

The robust calibration plan for Double Chooz has the main goals of determination of detection efficiency and energy scale. The detector response from the calibration is critical for Monte Carlo tuning, data analysis and systematic error determination [51]

4.8.1 Light Injection

The inner detector light injection system is embedded inside the detector on the PMT support structures. There are 46 light injection points throughout the detector (figure 4.23). 32 diffused light injection points and 14 pencil beam points. Three wavelengths are utilized, 425 and 475 nm for direct light and 380 nm for re-emission. Low intensity light injections are used for individual PMT gain calibrations. High intensity light injections are used for relative time offsets [70]. With the embedded

system, light injections can be easily implemented. Regular IDLI runs are part of the normal data taking sequence.

4.8.2 Source Deployment Systems

There are two integrated systems for the deployment of sources; gamma catcher guide tube and Z-axis. The gamma catcher guide tube is installed between the target and gamma catcher. Sources are mounted on a guide wire that is fed through the tube. The Z-axis deployment system allows for calibration sources to be deployed in the center of the target. The deployment is done through a glove box installed at the top of the target chimney to protect from contaminants from entering the target volume (figure 4.24).

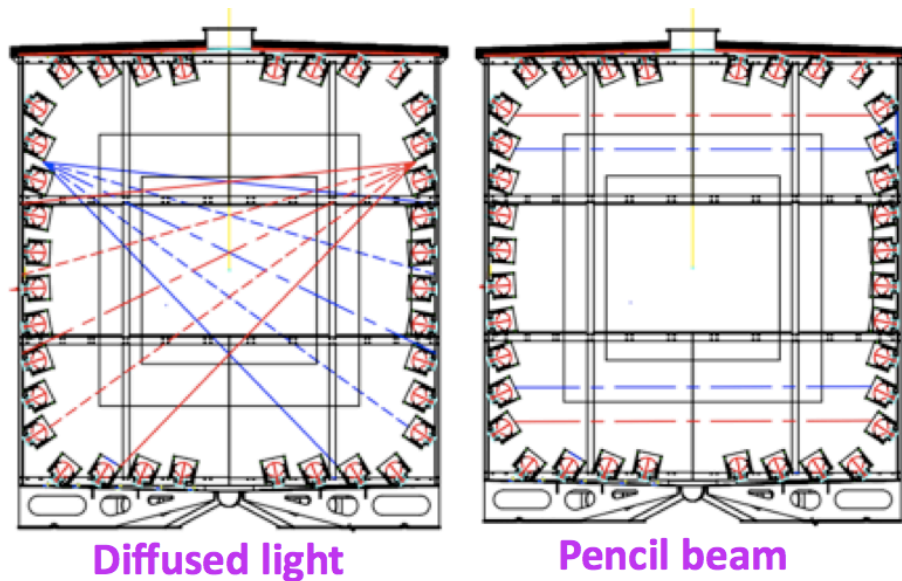


Figure 4.23: Illustration of the diffused (left) and pencil beam (right) light injection [70].

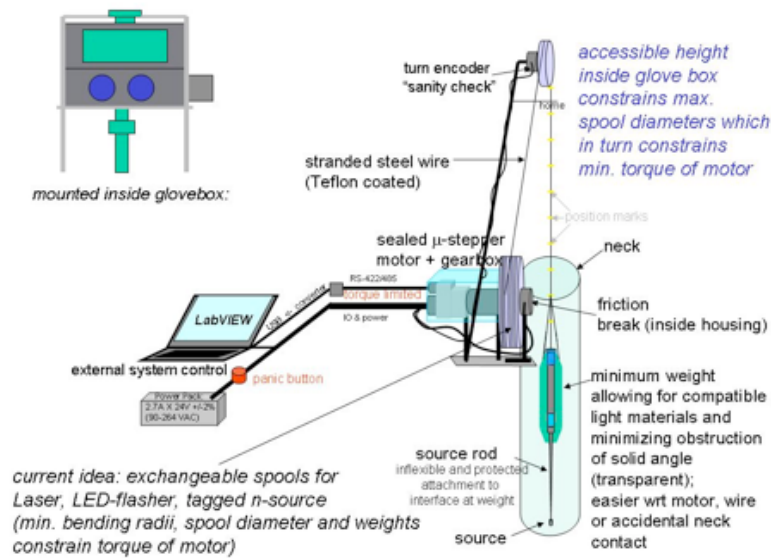


Figure 4.24: Schematic of the z-axis calibration source deployment system [64].

Chapter 4.9

Detector Installation

The Double Chooz far detector was constructed between May 2008 and June 2010. There were many challenges in building the DC far detector in a lab designed for the smaller CHOOZ detector. Because of spatial constraints, the inner veto and buffer vessels were brought into the lab in pieces and assembled as they were lowered into the detector pit. The commissioning of the data acquisition system began in June of 2010 with a “dry” detector. Because the target scintillator liquids can be degraded in the presence of water molecules the detector was flushed with nitrogen gas to remove any moisture. The filling of the detector was a delicate process because of the multi-layered volumes. Tolerances for height differences between the volumes was on the order of $\sim 5\text{mm}$ to ensure the integrity of the acrylic vessels.

4.9.1 PMT Testing Plan

As a contribution during detector construction, the University of Tennessee group implemented an onsite PMT testing plan during installation phases in 2009. The Inner Detector PMTs were originally delivered to Tohoku, Japan and Heidelberg, Germany for characterization studies. Upon completion of the acceptance and characterization testing the PMTs were assembled with acrylic housing and magnetic shielding. The PMTs would then be stored awaiting shipment to Chooz for integration. The goal of testing was to ensure that no damage occurred and that only properly operating PMTs were installed. The PMTs would be individually tested as part of the installation chain and again verified after installation.

To perform the testing a portable system was designed and built at the University of Tennessee. The testing system (figure 4.25) consists of a custom-built electronics platform, NIM crate (and modules), CAMAC crate (and modules), oscilloscope, and control computer. The computer used LabView software to interface with the CAMAC crate for data acquisition. The scope of the testing included visual checks of the PMT pulses with an oscilloscope, monitoring the short term behavior of the PMT dark current rate, and single photoelectron response. PMT dark currents are signals produced by photomultipliers in the absence of any light and are present in all PMTs. Electrons thermally emitted from the photocathode or dynodes primarily produce the dark current. The dark rate was monitored by a scaler receiving an input from a discriminator set at a threshold of $\frac{1}{4}$ SPE level of the PMT signal. The SPE spectrum was read by a charge sensitive ADC (analog to digital converter). Two electronic operational modes were developed to allow testing the PMT SPE response from self-triggering dark pulses (figure 4.26) or an external LED light source (figure 4.27).

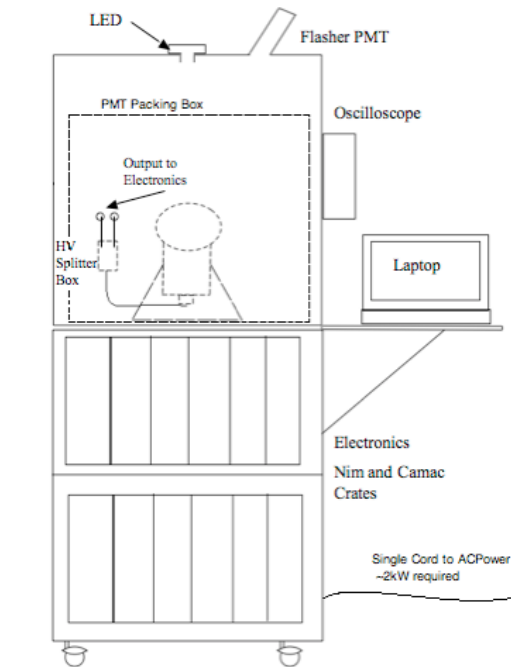


Figure 4.25: Portable testing system

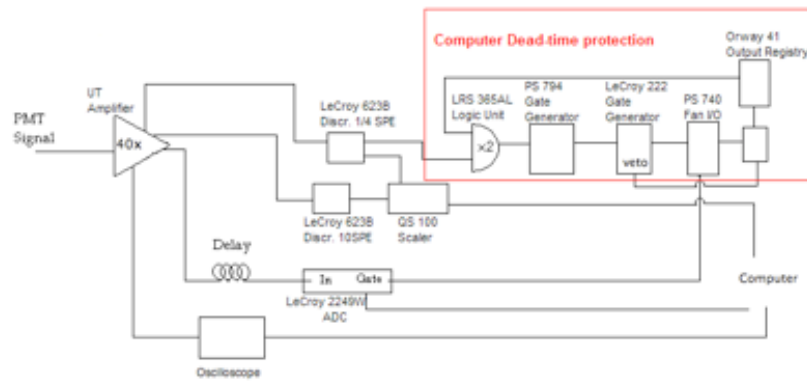


Figure 4.26: Data Acquisition diagram for self triggered testing mode.

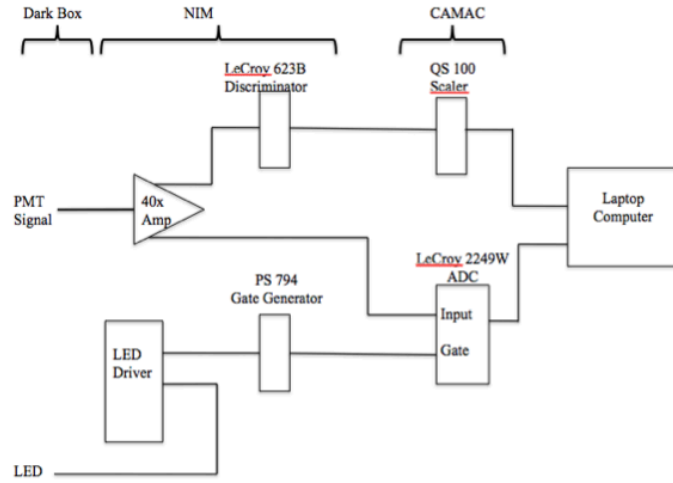


Figure 4.27: Data Acquisition diagram for LED testing mode.

4.9.2 Inner Veto PMT Testing

In addition to testing of the inner detector PMTs, tests were performed on the Inner Veto PMTs. The IV PMTs were encapsulated at the Eberhard-Karls Universitat Tübingen, Germany. The portable testing system was taken to Tübingen in the summer of 2008 to perform tests on the newly encapsulated PMTs. The 8-inch IMB PMTs have poor resolution to the single photoelectron peak because of the venetian blind dynode structure (figure 4.28). For this reason the PMTs were tested using a low intensity LED light source.

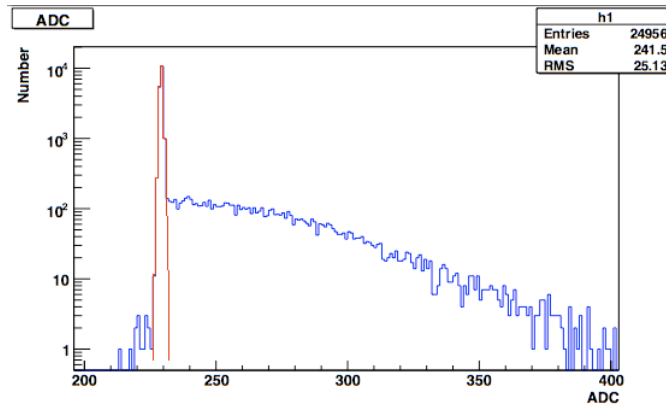


Figure 4.28: Single photoelectron spectrum for IV PMTs (pedestal is in red).

The relative gain is determined by calculating the mean value of adc entries above the pedestal,

$$G_{\text{rel}} = \frac{(Adc_{\text{mean}} - Adc_{\text{ped}}) \cdot \alpha \cdot 2}{q_e \cdot \text{Amp}} \quad (4.2)$$

where G_{rel} is the relative gain, Adc_{mean} is the mean adc (unit of digitized charge) above the pedestal, Adc_{ped} is the peak value of the pedestal, α is the charge/adc-channel conversion, q_e is the charge of the electron, and Amp is the amplification factor of the PMT signal. In addition the dark rate was monitored during the ~ 30 min testing period. The values measured during the tests in Tübingen were used for comparison during the onsite tests performed during IV PMT installation. The distribution of gain measurements from Tübingen and onsite are shown in figure 4.29. Two PMTs were rejected from onsite tests, one for unstable dark rate and one for no signal.

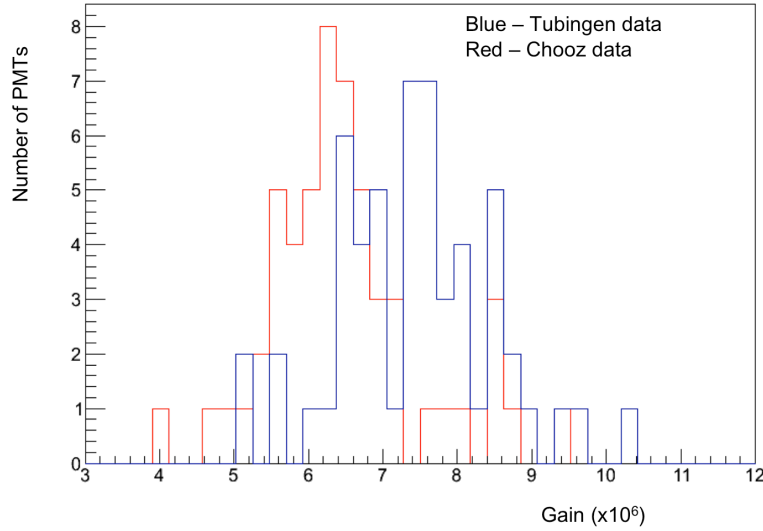


Figure 4.29: Measured gain distribution for IV PMTs

4.9.3 Inner Detector PMT Testing

The testing of the Inner Detector PMTs was performed during installation periods between May-June 2009 (wall and floor of the buffer) and November 2009 (buffer lid). Unlike the IV PMTs the inner detector PMTs exhibit strong single photoelectron resolution (figure 4.30). This allowed the use of the dark pulses for single photoelectron (spe) charge distribution measurements. To determine the gain a Gaussian fit is applied to the spe spectrum. The high voltage was set at the level determined by the characterization tests in Germany and Japan.

$$G = \frac{(Gaus_{mean} - Ped) \cdot \alpha \cdot 2}{q_e \cdot Amp} \quad (4.3)$$

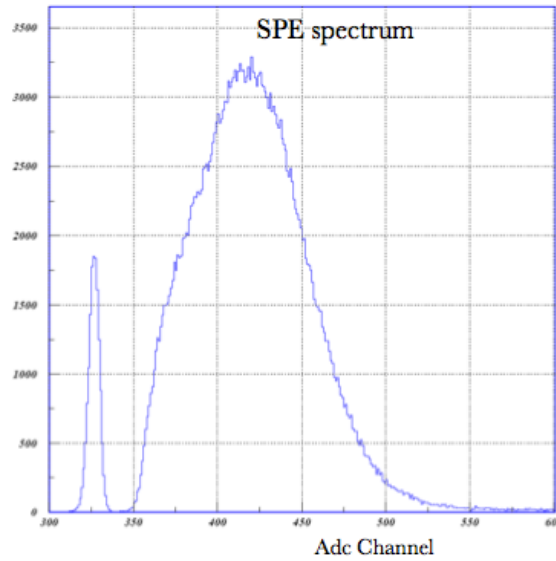


Figure 4.30: Single photoelectron spectrum for self-triggered inner detector PMT (the small peak on the right is the pedestal taken from a fixed external trigger).

The testing was performed as part of the first step of the installation chain (figure 4.31). To keep up with the tight installation schedule ~30 PMTs were individually tested each day. The tests were successful in identifying 5 problematic PMTs that were withheld from installation. Three PMTs exhibited abnormally high dark rates, one PMT had an unstable dark rate, and one PMT had poor spe resolution (figure 4.32)

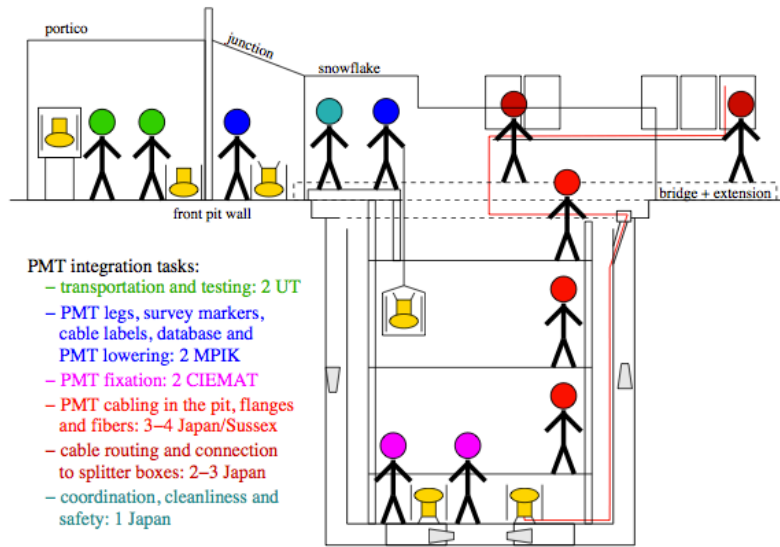


Figure 4.31: Overview of workflow during PMT installation (testing was performed in a clean tent outside of the detector pit).

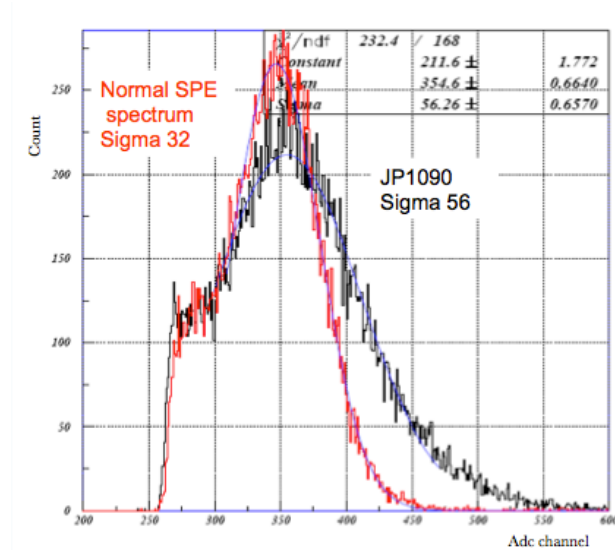


Figure 4.32: Comparison of normal spe distribution (red) and poor resolution (black).

4.9.4 DAQ Commissioning Support

During the DAQ commissioning support was provided with the use of the portable testing system used during PMT integration. For the safe operation of the PMT system, the detector must be fully isolated from outside light sources. Not only can outside light spoil data sets but also large amounts of light can damage the PMTs. The computer-controlled scaler was utilized in the checking for light leaks. The light leak checks were performed at various phases as new interfaces were installed at the detector. The scaler was also used during the tuning of the trigger system as a crosscheck of trigger rates. The independent data acquisition system was also utilized to pinpoint malfunctioning channels in the final DAQ. Portions of the portable testing system were made permanent fixtures in the DAQ system.

Chapter 5

Expected Signals

Chapter 5.1

Reactor Anti-neutrino Source

The source for any reactor anti-neutrino experiment originates from the beta decay of fission product inside the nuclear reactor core. As fission occurs inside of the reactor, neutron rich lighter nuclei are produced. These unstable products undergo a series of beta decays. Each fission results in roughly six anti-neutrinos produced. The four dominant fission isotopes in anti-neutrino production are ^{235}U , ^{239}Pu , ^{238}U , and ^{241}Pu . For reactor experiments the anti-neutrinos of energy above 1.8 MeV are of interest (table 5.1). The number of fissions is suitable for just a counting experiment. Due to the energy dependence of the oscillation probability it is useful to determine the energy spectrum of the produced anti-neutrinos. The spectrum of electron anti-neutrinos for ^{235}U , ^{239}Pu , and ^{241}Pu were measured from the beta spectrum of fission products [72,73]. The flux spectrum can be expressed as equation 5.1

$$\Phi_l(E_\nu) = \exp\left(\sum_{k=1}^{K_l} a_{kl} E_\nu^{k-1}\right) \quad (5.1)$$

where l represents the four isotopes and the parameters a_{kl} are given in reference [74] (figure 5.1).

Table 5.1: Number of anti-neutrinos (N_l) above 1.8 MeV and Energy released (E_l) per fission [74]

ℓ	N_ℓ^ν	E_ℓ [MeV]
^{235}U	$1.92(1 \pm 0.019)$	201.7 ± 0.6
^{238}U	$2.38(1 \pm 0.020)$	205.0 ± 0.9
^{239}Pu	$1.45(1 \pm 0.021)$	210.0 ± 0.9
^{241}Pu	$1.83(1 \pm 0.019)$	212.4 ± 1.0

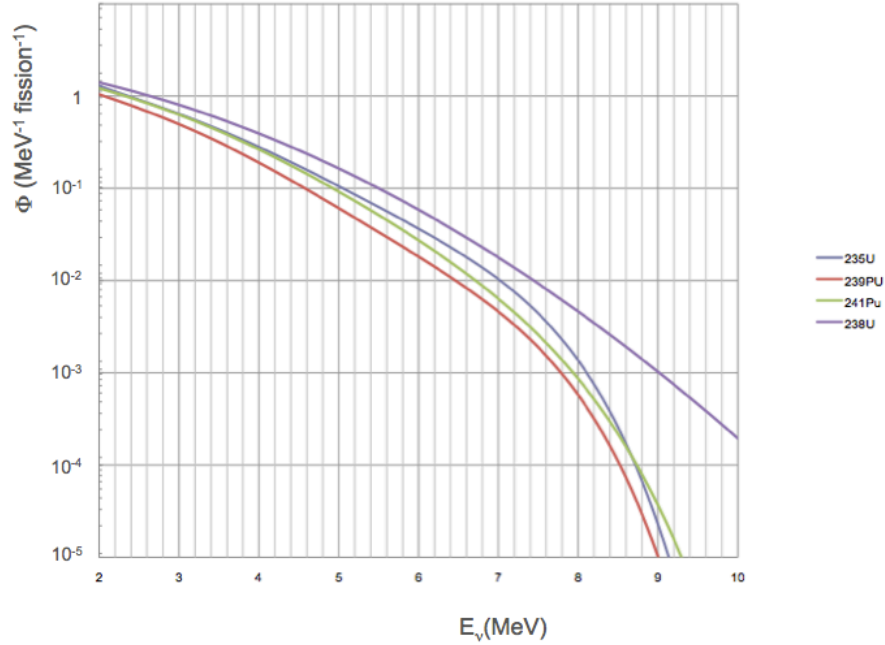


Figure 5.1: Anti-neutrino flux spectrum from fission products of ^{235}U , ^{239}Pu , ^{241}Pu , and ^{238}U .

The overall neutrino spectrum will depend on the composition of the reactor core and number of fissions in the reactor. At the Chooz-B reactors the average make up is 55.6% ^{235}U , 32.6% ^{239}Pu , 7.1% ^{238}U , and 4.7% ^{241}Pu [48]. During a burn up cycle the composition of the reactor core evolves. Detailed core simulations with MURE and DRAGON packages allow the prediction of the make up (figure 5.2) [75]. The number of fissions of the reactor is calculated from the reactor thermal power. In conjunction with Electricite de France (E.D.F) the thermal power is monitored (figure 5.3). The two reactors of the Chooz-B plant are 4.27 GW_{th} pressurized water reactors (PWR). The

majority of the power production comes from the fission of ^{235}U which releases 201.7 MeV per fission. The total energy per fission can be expressed as

$$\langle E_f \rangle_{tot} = \sum_l \alpha_l \langle E_f \rangle_l \quad (5.2)$$

where l is one of the four fission isotopes, $\{E_f\}_l$ is the average energy per fission for the isotopes (table 5.1), and α_l is the ratio of fissions

$$\alpha_l = \frac{f_l}{\sum_l f_l} \quad (5.3)$$

the f_l values are determined from the reactor fuel composition (figure 5.2) [75].

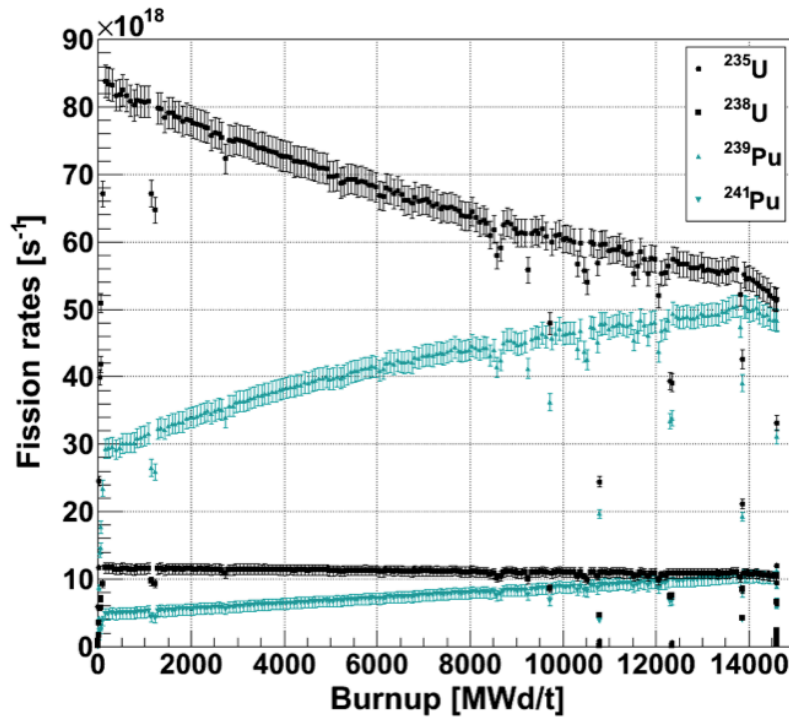


Figure 5.2: Simulated reactor core composition during a fuel cycle [76].

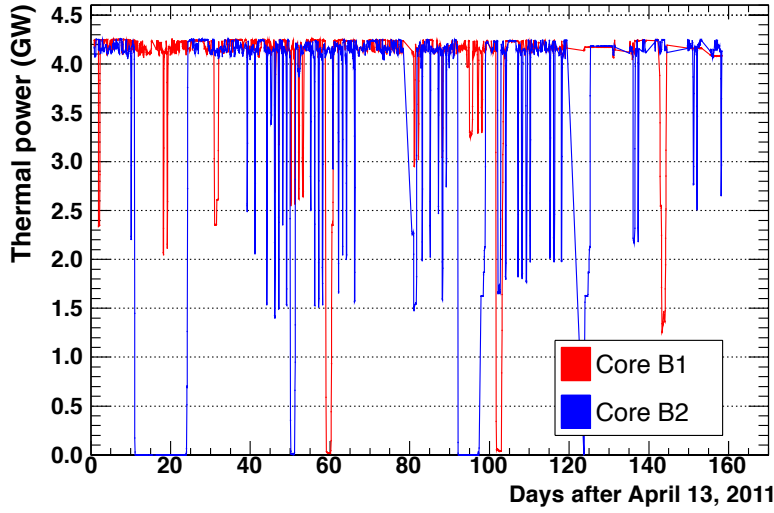


Figure 5.3: Thermal power from the two Chooz reactors [76].

Chapter 5.2

Inverse Beta Decay

The detectable signal, as with other reactor anti-neutrino experiments, comes from the products of the weak charge-current reaction inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (5.2)$$

The positron is almost immediately thermalized and annihilates with an electron producing two 0.511 MeV gammas. The energy deposited by the positron plus the two gammas is the IBD prompt signal. After 30 μ s the neutron is captured on Gd producing ~ 8 MeV in gamma rays that serve as the delay signal. In first approximation the threshold for the inverse beta decay interaction can be determined with the assumptions that the kinetic energy of the proton and neutron and mass of the neutrino are negligible.

$$E_{thr} = M_n - M_p + m_e \approx 1.8 \text{ MeV} \quad (5.3)$$

The visible energy of the prompt signal is related to the energy of the positron and mass of the electron.

$$E_{vis} = E_{e^+} + 2m_e \quad (5.4)$$

This can be related directly back to the incident electron anti-neutrino using the same assumption of negligible kinetic energy of the proton and neutron.

$$E_{e^+} = E_{\bar{\nu}} + M_p - M_n \quad (5.5)$$

$$E_{vis} \approx E_{\bar{\nu}} - 0.782 \text{ MeV} \quad (5.6)$$

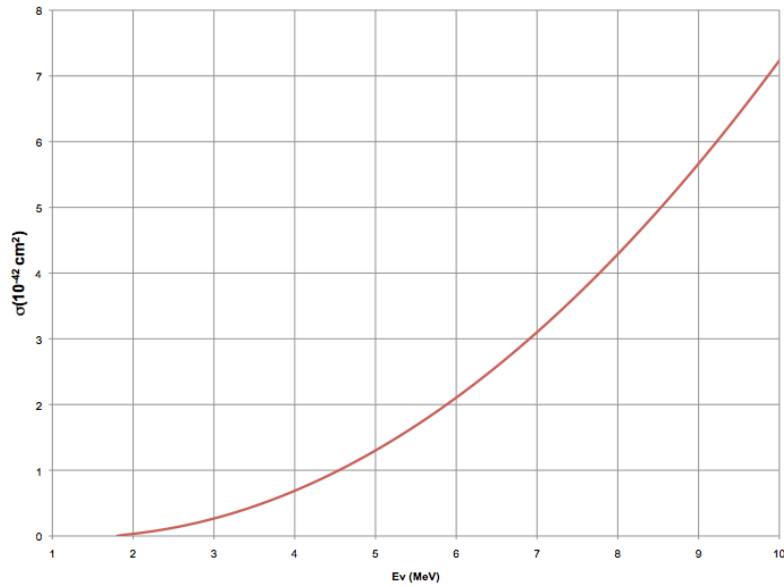


Figure 5.4: IBD cross-section with respect to electron anti-neutrino energy.

The inverse beta decay cross-section as a function of the electron anti-neutrino energy is (figure 5.4)

$$\sigma(E_{\bar{\nu}}) = K \cdot (E_{\bar{\nu}} + M_p - M_n) \sqrt{(E_{\bar{\nu}} + M_p - M_n)^2 - m_e^2} \quad (5.7)$$

where $K = (9.559 \pm 0.009) 10^{-44} \text{ cm}^2 \text{ MeV}^{-2}$, and is extracted from the neutron lifetime [51]. It is useful to calculate the mean cross-section per fission. Using equations 5.1, 5.2 and 5.7, the mean cross-section per fission is

$$\langle \sigma_f \rangle = \sum_l \alpha_l \langle \sigma_f \rangle_k = \sum_l \alpha_l \int_0^\infty \Phi_l(E_{\bar{\nu}}) \sigma(E_{\bar{\nu}}) \quad (5.8)$$

The total number of number of expected anti-neutrinos in the i energy bin (with no oscillation effects) can be expressed as [75]

$$N_{i,t}^{\text{exp}} = \frac{\varepsilon N_p}{4\pi} \sum_R \frac{P_{th}^R}{L_R^2 \langle E_f \rangle_R} \frac{\langle \sigma_f \rangle_R}{\left(\sum_l \alpha_l^R \langle \sigma_f \rangle_l \right)} \sum_l \alpha_l^R \langle \sigma_f \rangle_l^i \quad (5.9)$$

ε is the detector efficiency, N_p is the number of target protons (atoms of Hydrogen), R (1,2) represents the two reactors, L_R is the distance to reactor R . All other terms are defined in equations 5.2, 5.3, and 5.8. The summation of all bins gives you the total neutrino flux (figure 5.5).

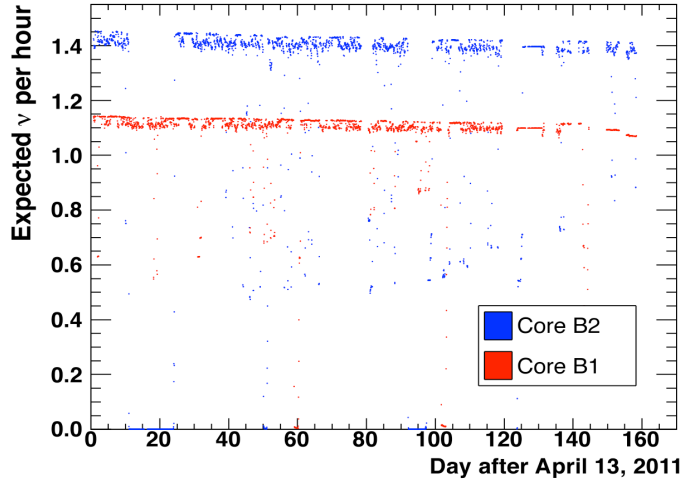


Figure 5.5: Expected un-oscillated electron anti-neutrino rate [76].

For the systematic uncertainty it is important to accurately know the number of free protons in the target vessel. The number of free protons available can be determined by precisely measuring the number of hydrogen atoms in the target. During the filling of the far detector a weighing tank was used as an intermediate vessel to determine the total mass of the target liquid, which is total mass (m_t) is 8288.0 ± 3 kg. The following formula is used to determine the number of hydrogen atoms

$$N_H = (m_t * f_H) / m_H \quad (5.10)$$

where f_H is the mass fraction of hydrogen (13.6 ± 0.04 %) and m_H is the mass of hydrogen. The resulting number of hydrogen atoms is $6.747 \pm 0.02 \times 10^{29}$ [77].

Chapter 5.3

Backgrounds

Any non-IBD event that shares the same energy and timing aspects is called a background event. The background events can mimic the IBD prompt and delay signals. The backgrounds originate from radioactive decay and muon induced events.

5.3.1 Accidental

Radioactivity from the rock surrounding the detector or from materials used to build the detector (primarily PMTs) is always present. As described in chapter 4, the design of the detector and choice of materials allows for the mitigation of much of the radioactivity. The majority of accidental prompt signals originate from the decay of ^{40}K and chains of ^{238}U and ^{232}Th . A fraction of these decays can produce a prompt like signal in the positron signal range. The radioactive signal that is followed by neutron capture can produce an IBD-like pair. The neutrons are primarily from untagged muons that produce neutrons reaching the target vessel of the detector. The accidental background was expected to be ~ 2 events per day for the DC far detector [51]. Accidental events can be estimated from the singles rate in the prompt and delay energy range. In the data off-time prompt-delay coincidence window precisely measured the accidental background.

5.3.2 Correlated ^9Li

High-energy cosmic ray muons interacting with ^{12}C produce a number of radioactive isotopes (table 5.2). Organic scintillators are susceptible to the creation of these isotopes. The ^9Li isotope is of particular interest because of the beta-n decay modes (figure 5.6). Roughly 50% of the ^9Li decays produce an electron followed by a neutron. The energy deposit of the electron is in the IBD positron energy range can be in coincidence with the neutron capture on Gd. This signal mimics an IBD event. With a half-life of 178ms, a veto window after muons long enough to avoid ^9Li is not feasible because of the dead time it would introduce based on the muon rates of $\sim 13\text{Hz}$ in the inner detector (discussed in chapter 6.3). Information from tagged muons that enter the target volume can be used to differentiate IBD and ^9Li events.

Table 5.2: Muon induced isotopes in organic scintillator [78]

	Isotopes	$T_{1/2}$	$E_{\max}$ (MeV)
β^-	^{12}B	0.02 s	13.4 (β^-)
	^{11}Be	13.80 s	11.5 (β^-)
	^{11}Li	0.09 s	20.8 (β^-)
	^9Li	0.18 s	13.6 (β^-)
	^8Li	0.84 s	16.0 (β^-)
	^8He	0.12 s	10.6 (β^-)
	^6He	0.81 s	3.5 (β^-)
β^+, EC	^{11}C	20.38 min	0.96 (β^+)
	^{10}C	19.30 s	1.9 (β^+) (+0.72 MeV γ , 98.53%)
	^9C	0.13 s	16.0 (β^+)
	^8B	0.77 s	13.7 (β^+)
	^7Be	53.3 d	0.478 (γ , 10%)

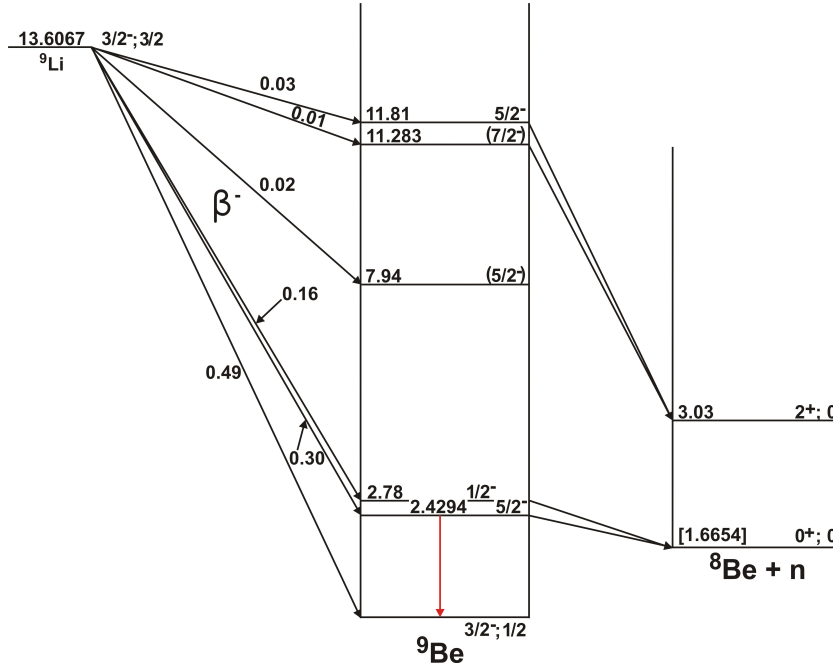


Figure 5.6: Decay chain of ^9Li [79].

5.3.3 Muon induced Fast Neutrons

Muons that pass near the detector, outside of the inner veto, can produce correlated backgrounds. Muon spallation occurs when high-energy muons interact with nuclei. An exchange of a virtual photon results in nuclear disintegration with the emission of a neutron [80]. The fast neutrons can enter the gamma catcher or target volumes of the detector because of their large interaction length. A false IBD coincidence can occur if the neutron produces a recoil proton followed by capture on Gd. The steel shielding provides some protection, but not total, from the fast neutron events. The proton recoil energy distribution is flat and extends to a range well above the IBD positron spectrum. This allows for investigation above ~ 12 MeV to extrapolate the fast neutron background in the IBD range.

Chapter 6

Detector Response

Data taking officially started for the Double Chooz far detector on April 13, 2011. The first publication data set was through September 18, 2011. During this time 2594 one-hour data runs were taken for a total run time of 101.5 days (figure 6.1). The data taking efficiency and analyzed runs are shown in figure 6.2.

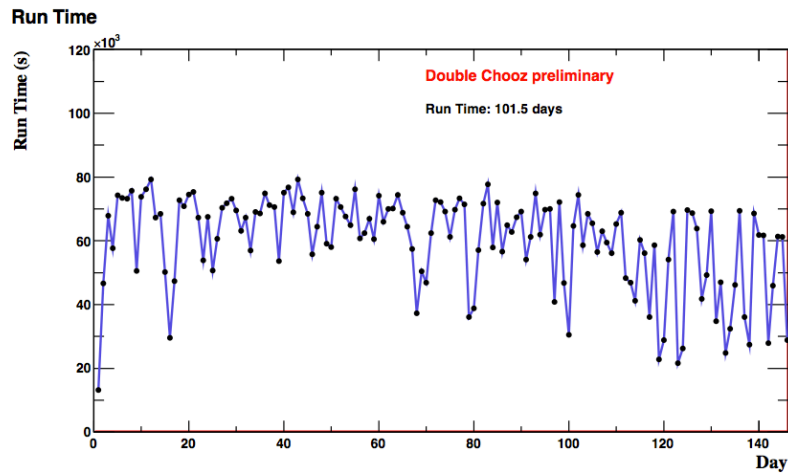


Figure 6.1: Run time per day (day 0 is April 13, 2011)

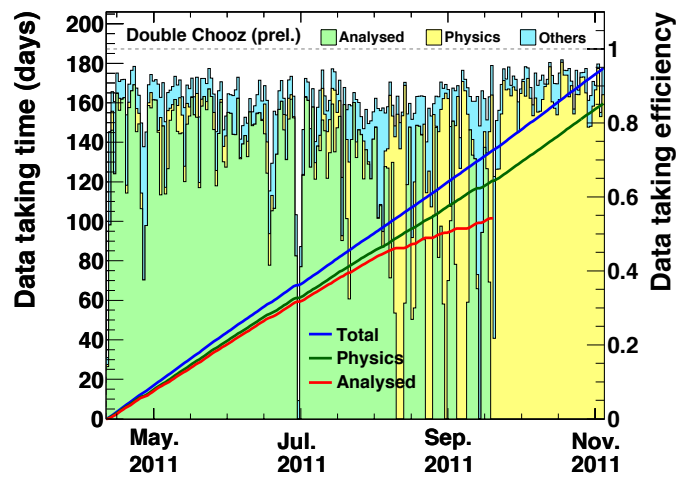


Figure 6.2: Data taking efficiency for DC far detector

Chapter 6.1

Trigger Efficiency

The trigger system, described in Chapter 4.5.2, generates the trigger based on energy deposition conditions of FEE stretcher pulses. In conjunction with the FADC, the goal was to introduce no hardware dead time to the data acquisition system. To determine the efficiency of the trigger the prescaled and stretcher input was analyzed. The efficiency is determined by comparing the stretcher amplitude with the trigger release timing. The examination found that the trigger is 100% efficient (with and uncertainty of 0.4%) above 0.7 MeV (figure 6.3). A cross check of the trigger efficiency was performed using source calibration data. A comparison of MC and data for ^{137}Cs source deployment was in agreement with the previous efficiency determination [81].

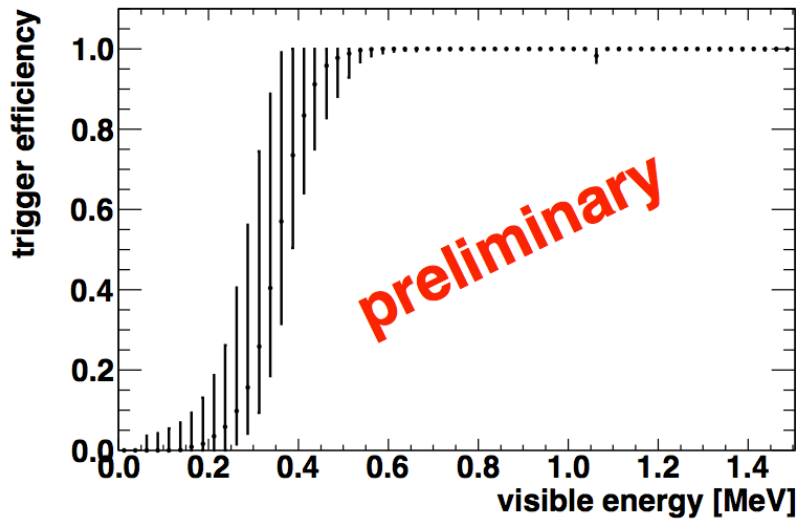


Figure 6.3: Trigger efficiency verses reconstructed energy [81]

Chapter 6.2

Instrumental Light Noise

During the early stages of the Double Chooz far detector, abnormally high trigger rates were observed. Both the stand-alone testing electronics and the trigger board of the DAQ confirmed these rates. The high rates were unexpected with no scintillator liquids in the detector volumes. Figure 6.4 shows the results of the trigger scan [82]. The magenta line shows symmetric noise from induced signals in the cables. The blue line shows asymmetric noise, which indicates a true PMT signal. The red line shows the neutrino signal threshold. A rate of ~ 250 Hz was unexpected for a dry detector.

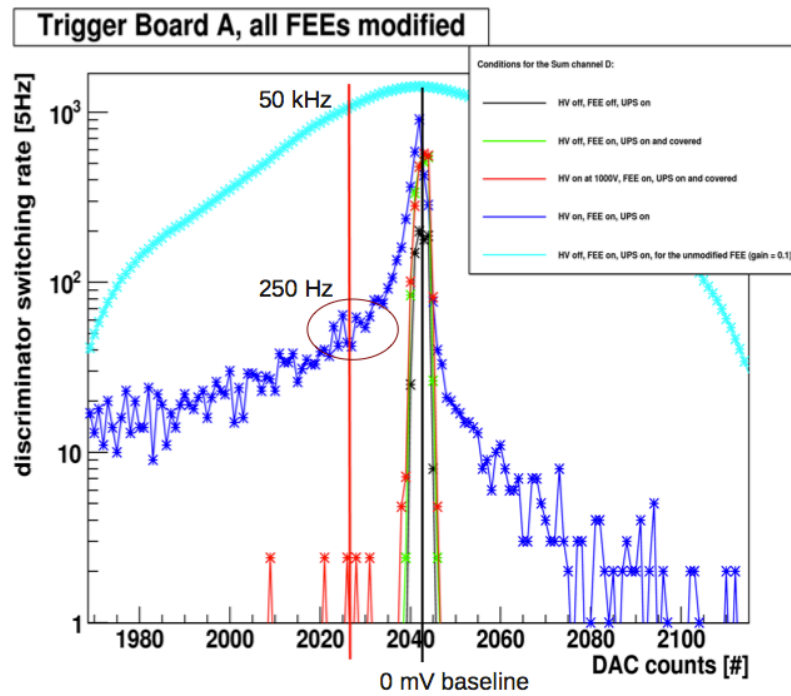


Figure 6.4: Trigger rate scan for the DC far detector with no scintillator liquids [82].

The x-axis is the digital threshold units of the trigger system with the baseline shown as the black line and the ~ 0.5 MeV threshold shown as the red line.

The complete DAQ was not yet fully commissioned so an investigation of the high rates was performed by University of Tennessee using the portable testing system. The portable system could handle 16 PMT inputs at any time (figure 6.5). Each separate channel was received amplification of 10x and discriminated at $\frac{1}{4}$ the SPE level. The discriminator, CAEN model N845, sum output channel provides a pulse of amplitude proportional to the number of channels over threshold [83]. This signal is then discriminated based on the multiplicity of events. The tests were performed primarily with a set of 16 PMTs located on the floor of the buffer vessel (similar results were found for separate sets of PMTs). Initial investigation found that $\frac{1}{3}$ of the channels showed signs of noise in the channels. The overall noise was uncorrelated and was not responsible for the high trigger rate. Tests were also performed with the lab darkened to eliminate light leaks as a source of the triggers. It was determined that light was not introduced into the detector from the lab.

For a ~ 0.5 MeV equivalent trigger a threshold was set for 4 of the 16 PMTs. The rate for the 4 fold multiplicity condition was ~ 120 Hz with all 390 PMT channels at nominal high voltage (high voltage value for 10^7 gain). With the high voltage on to only

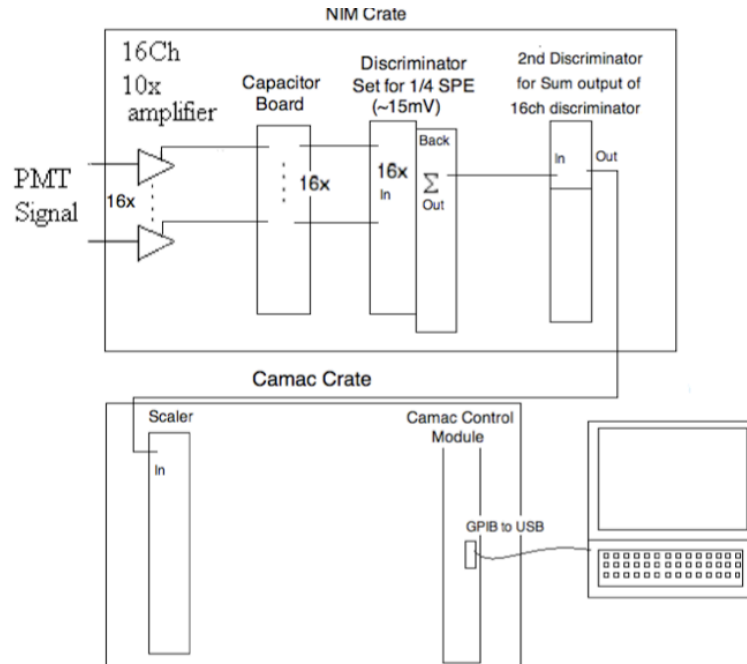


Figure 6.5: Testing electronics configuration

the 16 monitoring PMTs the rate dropped to 11 Hz. A scan of the multiplicity conditions was performed with all PMTs and only 16 PMTs at nominal high voltage (figure 6.6). Oscilloscope traces were taken for the coincidence events (figure 6.7). The pulses appeared to be multiple photoelectrons, which spanned 100 – 200 ns in duration. Additional scans were performed of the rate dependence on the number of PMTs turned on (figure 6.8).

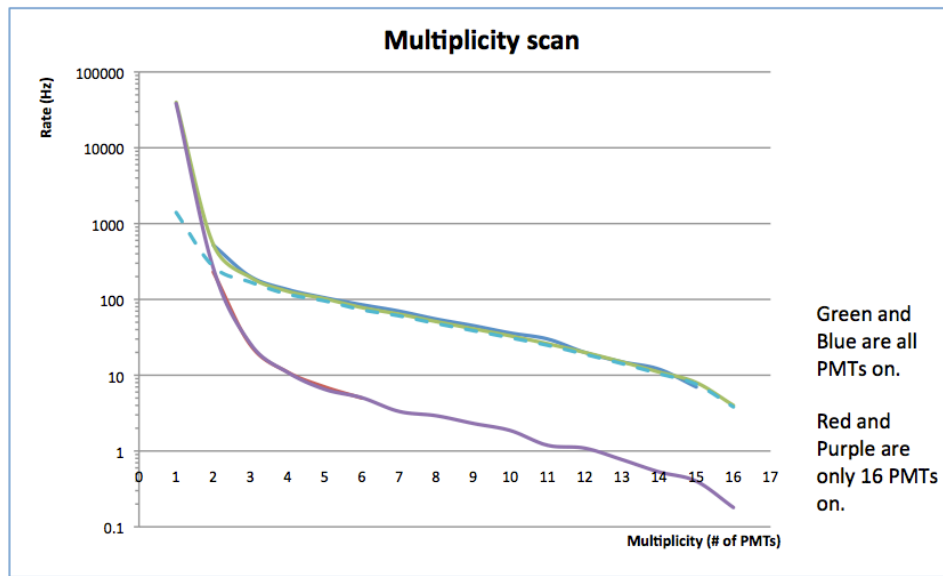


Figure 6.6: Trigger rate multiplicity scan

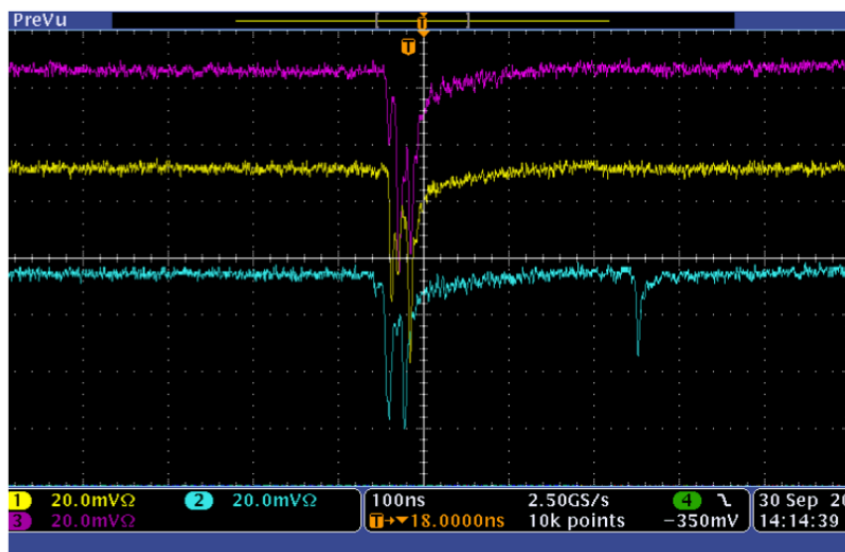


Figure 6.7: Oscilloscope pictures of light noise events

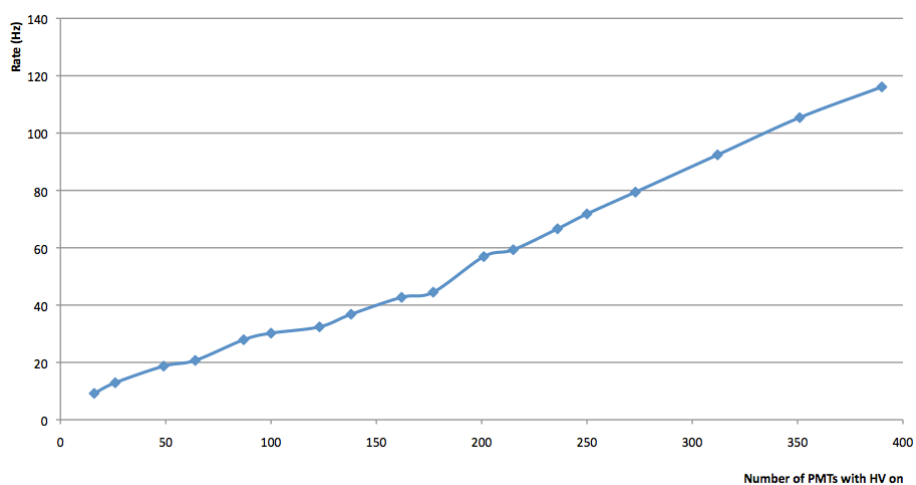


Figure 6.8: Trigger rate verses number of PMTs under nominal high voltage.

A clear correlation was found between the rate and the number of PMTs turned on. The next tests were to examine the high voltage dependance on the light noise events. The 16 monitoring PMTs remained at nominal high voltage as all of the other PMTs were brought up to nominal high voltage. The rate was taken as the high voltage was ramped up at 20 V/s. The high voltage dependence of the noise rate could be seen as the PMTs reached the nominal high voltage value. Additional red points are for all PMTs at a set high voltage (figure 6.9).

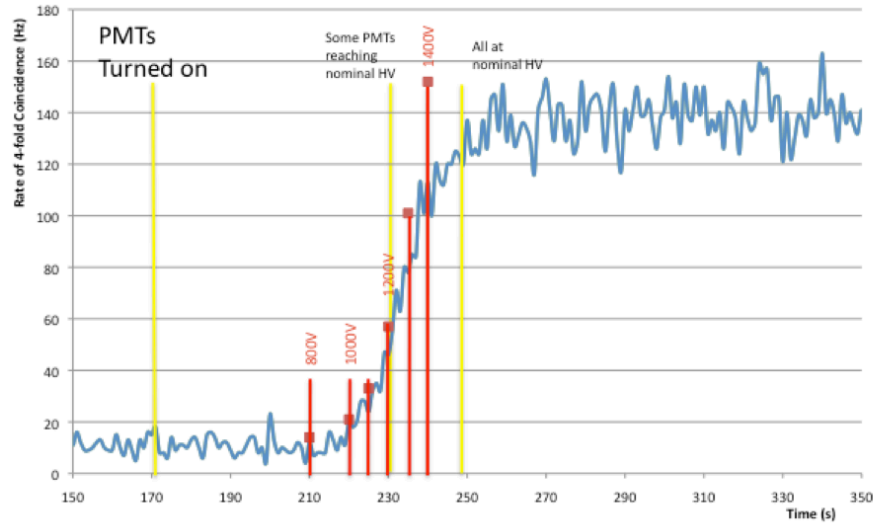


Figure 6.9: Trigger rate progression with time as the high voltage is ramped up.
Red points are separate measurements with all PMTs at HV indicated.

From these tests, it was determined that the PMTs were the source of the high trigger rate. The oscilloscope pictures showed that it was detected light and not electronic noise. The light arrived in bursts that could be in duration of several hundred nanoseconds. It appeared that all PMTs were contributing to the light noise rates and that there was a clear high voltage dependence on the rate.

After the discovery of the light noise originating from the PMTs in the far detector, several tests were performed at labs in Tohoku University in Japan, MPIK in Germany, CIEMAT in Spain, and LLNL in the US. The goal was to properly characterize the nature of the light emission. From these test it was found that the origin of the light was the base of the PMT. These independent studies determined that light is originating in the PMT base circuit, which is potted in clear epoxy (figure 6.10). The light production has been well characterized from studies performed with detector data and at labs outside of Chooz. The pulsed light emissions (or glowing) occur for all PMTs at differing rates and intensities. The rate of light emission shows a dependence on the applied high voltage (figure 6.11) and PMT ambient temperature. The rate is unstable with time with sudden increases and decreases in glowing rates per PMT observed. PMT pulses for glowing events typically have a long duration of over 100 ns with an intensity that can range up to hundreds of photoelectrons.



Figure 6.10: Picture of the DC inner detector PMT base.

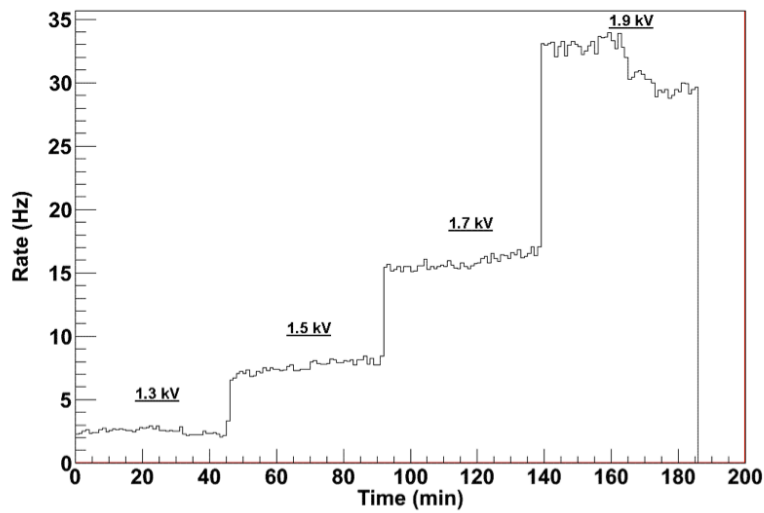


Figure 6.11: HV dependence of glowing rate for single PMT [84].

It was observed that within the epoxy some air bubbles had formed over areas of the circuit board. It is thought that the dielectric properties of the epoxy cause a polarization around the small air bubbles. As the electric field becomes strong enough a coronal discharge can occur in the trapped gas [84].

Inside the detector, the PMTs face the reflective wall of the buffer structure and are surrounded by reflective magnetic shielding. The magnetic shield does provide some optical shielding from neighboring PMTs. Light must reflect off the buffer wall in order

to be detected by other PMTs. As the light exits the base of the PMT, a large portion is reflected back onto the glowing PMT's photocathode. There is also evidence that some light exits out of the front of the PMT. This means that the glowing PMT will often collect a large amount of charge from the light emission.

Multiple strategies in hardware and analysis have been implemented to deal with the unexpected light noise. The most utilized feature of the glowing is that a large portion of light is detected by the glowing PMT. The trigger system has 24 input channels, 16 PMTs per channel that are individually discriminated. The individually discriminated channels do not determine the trigger condition but the multiplicity of channels above a discriminated value is recorded. For many lower amplitude light noise events, the glowing PMT collects almost all of the light. If the light collected for the single PMT can exceed the trigger threshold then multiplicity of 16 channel groups will be one. An isotropic light distribution is found for scintillation events in the GC and target and should result in multiple groups above the threshold. To eliminate a large portion of the light noise the multiplicity must be greater than one.

In order to take advantage of the high voltage dependence of glowing rate the high voltage for all PMTs was reduced. The reduction of $\sim 100\text{V}$ lowered the gain to $5/6$ the original level. In addition, the 14 PMTs with the highest glow rates were turned off. The reduction in high voltage and turning off the PMTs with the highest glow rates reduced the overall rate by $\sim 40\%$.

Software cuts are used to remove the remaining light noise events from data. The cuts were based on two features of the glowing events, charge collection of the glowing PMT and wide time spread of glowing events. The ratio of maximum charge (of a single PMT) to the total charge of the event (MQTQ ratio) has been useful in the reduction of glowing events from the data set (figure 6.12). The optimal cut was determined to be when a single PMT collected $> 9\%$ of the total charge for IBD prompt like events (0.7 – 12 MeV) and $> 6\%$ for delay energy range (6-12 MeV). The characteristic long pulse duration was also used for data cuts. Pulses originating from the target should reach the

PMTs within a narrow time frame. The light from glowing events is emitted over a time window of a few hundred nanoseconds resulting in a larger spread in the start time of the detected pulses. The RMS of the pulse start time (RMSTstart) will be greater than 40ns for light noise events (figure 6.13). The prescribed cuts only eliminate negligible fraction of MC generated IBD events (figure 6.14). All other data analysis is assumed to have light noise cuts applied.

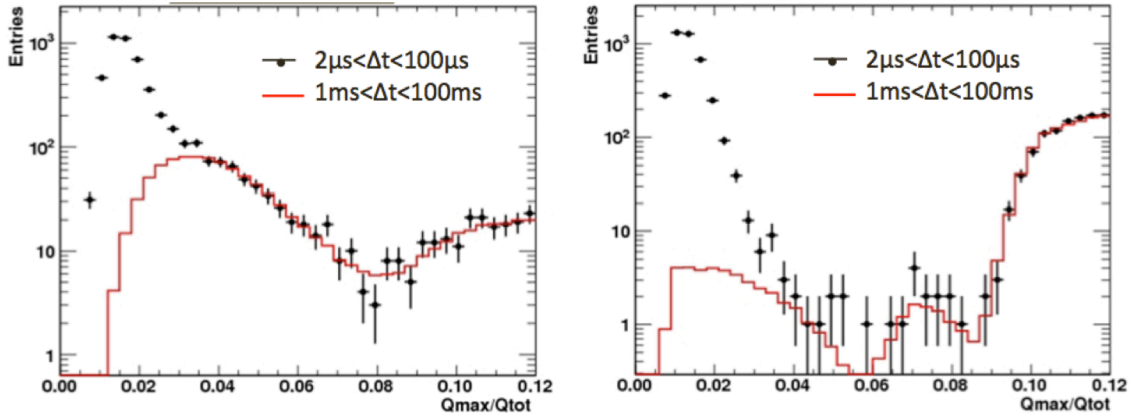


Figure 6.12: MQTQ distribution for prompt-like events (left) and delay-like events (right) pairs.
Black points are pairs with Δt 2-100 μ s, Red points are scaled events with Δt between 1-100ms

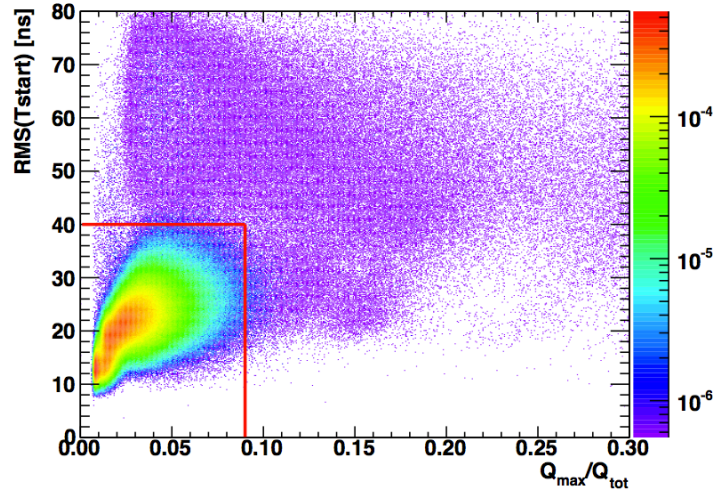


Figure 6.13: RMS(Tstart) verses Qmax/Qtot variables used for light noise rejection.
Red box indicates cut selection for good signals.

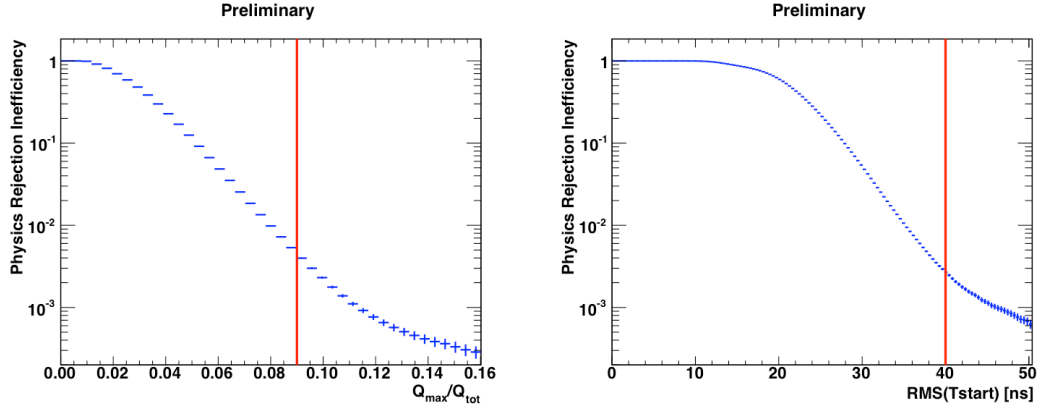


Figure 6.14: Light noise cut inefficiency for $Q_{\max}/Q_{\text{tot}}$ (left) and $\text{RMS}(T_{\text{start}})$ (right).

Red lines are light noise cut values.

Chapter 6.3

Muon Data

Muons can induce a number of background events, primarily from spallation neutrons. Muons are tagged by the inner veto from the light produced in the IV liquid scintillator. The inner veto energy spectrum is given in figure 6.15. The peak at ~ 200 MeV represents muons through going the inner volume depositing energy on two sides of the veto. The small peak at ~ 100 MeV represents muons entering one side of the detector inner volume but not exiting. The high-energy tail is from muons traveling vertically along the inner veto volume. The classification of muons is important for understanding backgrounds resulting from muons. Muons entering the inner detector are of interest due to the production of long-lived isotopes. Figure 6.16 shows the inner detector muon spectrum. The rates for muons entering the inner veto and inner detector are 46Hz and 13Hz, respectively (figure 6.17). To limit the backgrounds caused by muons, a 1ms veto is applied to events following tagged muons for IBD searches.

Energy spectrum for muon events in the Inner Veto

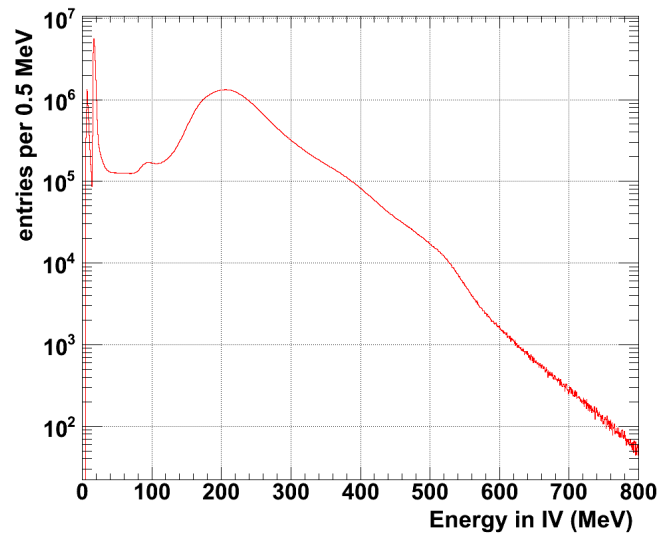


Figure 6.15: Energy spectrum of IV events

Energy spectrum for muon events in the Inner Detector

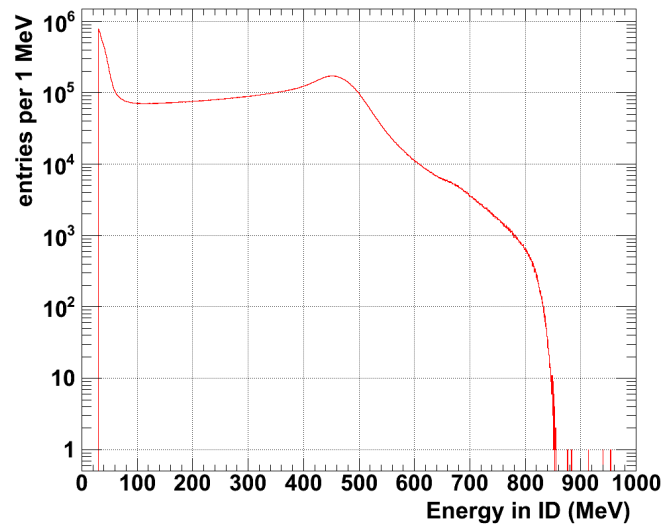


Figure 6.16: Energy spectrum of ID muons

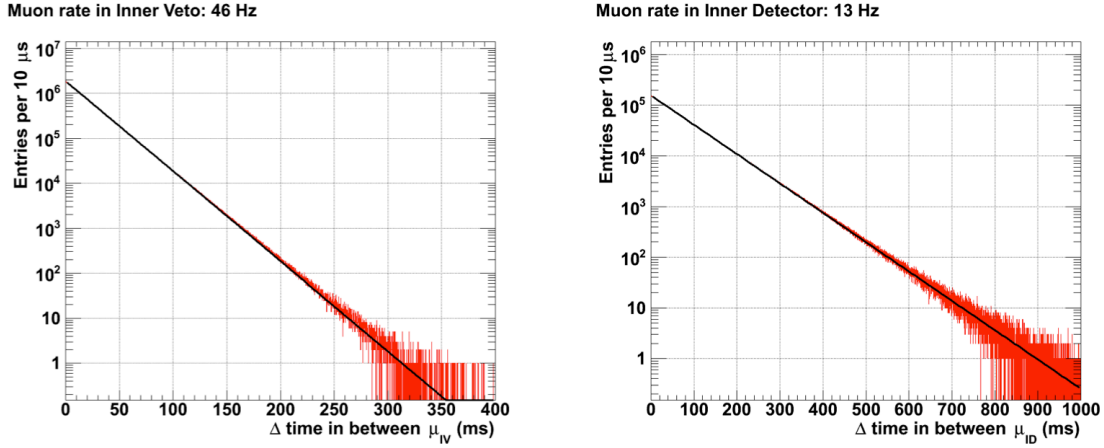


Figure 6.17: Muon rates for inner veto (left) and inner detector (right)

The detection of neutrons following a muon has actually been a useful tool for determination energy scale and scintillator stability. By looking at all events following muons (0.2-1ms) an energy peak of neutron capture on hydrogen is present (figure 6.18). An off time window (1.2-2ms) is used to subtract uncorrelated events. The time variation plot of the peak energy position shows a typical deviation of less than 1% over the analyzed data set (figure 6.19) [85]. The shift in the peak energy around day 20 corresponds to an unexpected power cut in the lab. The power cut lead to some slight instability in the PMT high voltage and gain.

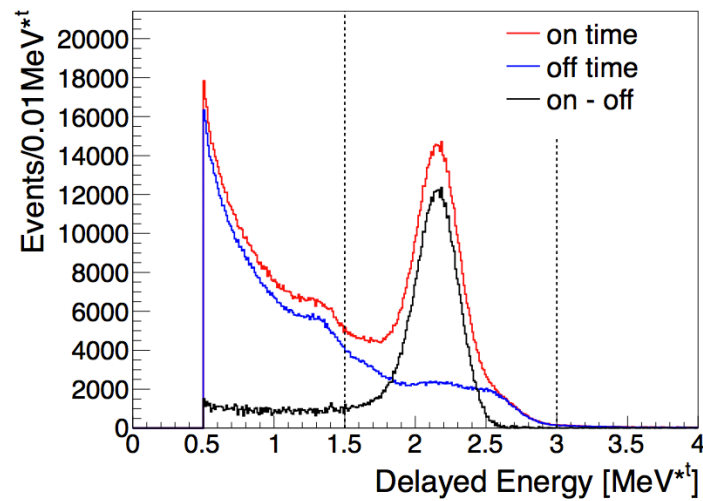


Figure 6.18: Energy peak for neutron capture on Hydrogen following muon events [85]

MeV^{*t} is the energy scale determined from reconstructed number of photo-electrons.

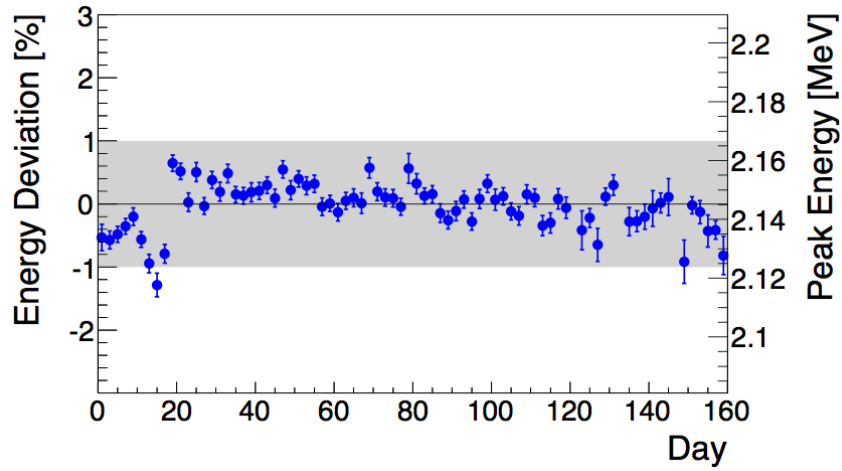


Figure 6.19: Time variation of peak energy of n-H capture [85]

Chapter 6.4

Singles Rate

The singles rate is the total number of events within the energy range of both the inverse beta decay prompt and delay events. Cuts are applied to remove light noise events and veto events following muons to evaluate the singles. The energy range for prompt-like events is from 0.7 to 12 MeV. The energy spectrum for prompt events (figure 6.20) is dominated by radioactive contamination. Two features in the energy spectrum can be seen around 1.4 MeV and 2.6 MeV. The 1.4 MeV bump correspond to gammas rays from the decay of ^{40}K . The 2.6 MeV bump is from the decay of ^{208}Tl , which is part of the thorium decay chain. Both of these are expected background signals. For the original CHOOZ experiment the singles rate was $\sim 130\text{Hz}$ [51]. With the improved shielding and choice of radiopure materials the singles rate for Double Chooz is $7.625 \pm 0.001\text{Hz}$ (figure 6.21). The rise in the singles rate around day 130 was due to uncharacteristic light noise in a single PMT. The PMT was turned off and runs affected by this PMT were omitted for the further analysis.

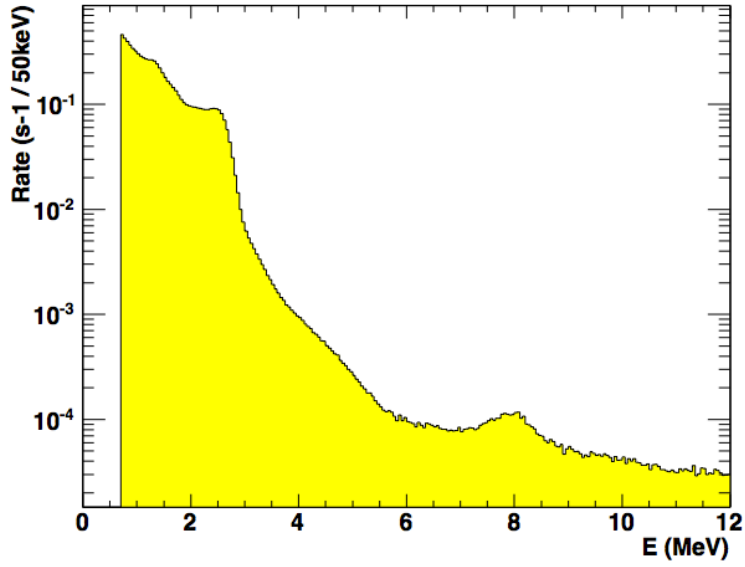


Figure 6.20: Energy spectrum of prompt-like singles events

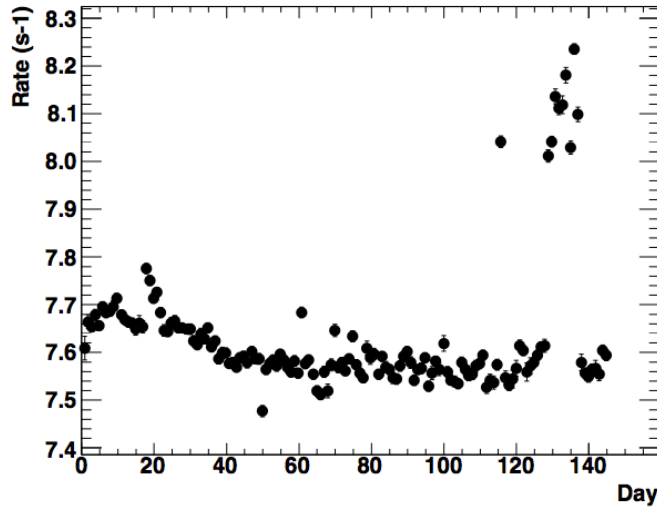


Figure 6.21: Prompt-like singles rate by day for Double Chooz

The delay-like singles are found in an energy range of 6 to 12 MeV. The energy spectrum (figure 6.22) shows a peak around 8 MeV. This peak is consistent with neutron capture on Gd. These neutrons originate from untaged muons. The rate for delay-like

events (figure 6.23) is 0.00743 ± 0.00003 Hz. From the rates of the prompt-like and delay-like events the accidental coincidence rate can be estimated.

$$R_{\text{acc}} \approx R_p * R_d * \Delta t = 0.48 \text{ day}^{-1} \quad (6.1)$$

Δt is the size of the coincidence window for IBD events.

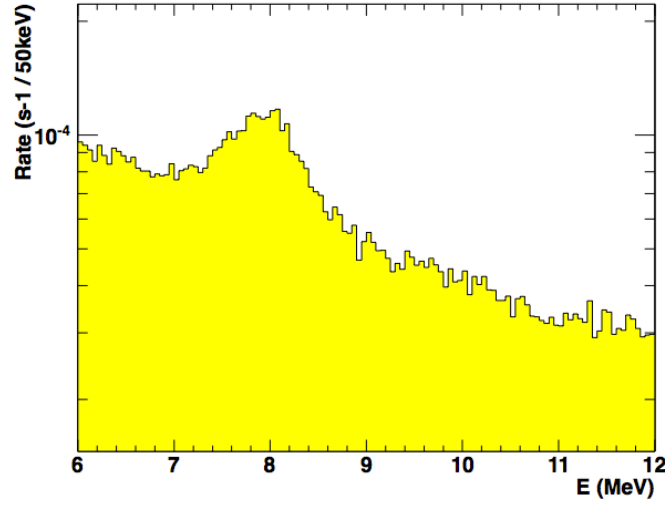


Figure 6.22: Energy spectrum of delay-like singles events

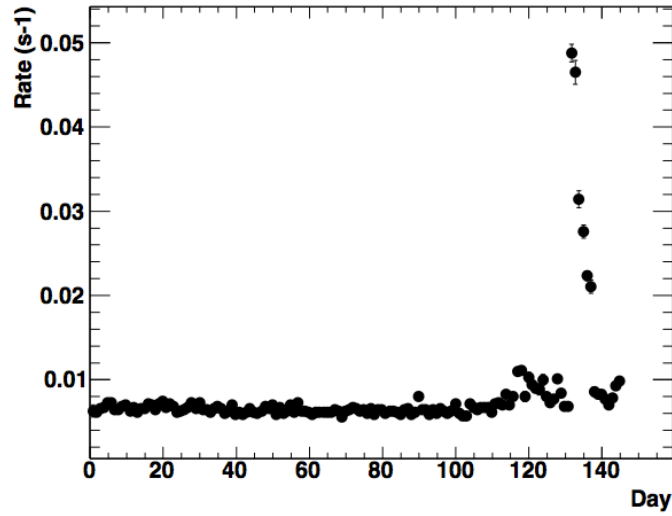


Figure 6.23: Delay-like singles rate by day for Double Chooz

Chapter 6.5

Calibration Data

6.5.1 Inner detector light injection

The IDLI system has been a crucial tool for characterizing the detector response. The IDLI is used frequently to determine individual PMT characteristic. For proper energy reconstruction the gains of the PMTs must be determined. Instabilities in the gain, illustrated in figure 6.17, can occur due to many factors such as power failure in the lab, temperature changes, or fluctuations in the DAQ electronics. IDLI runs, which are part of the normal data taking sequence, provide the parameters for gain adjustments applied to data.

The gain is extracted using low intensity IDLI runs. The low intensity runs produce signals from the PMTs of one or two photoelectrons (PE). The gain is found by fitting the charge distribution (figure 6.24) with the function

$$F(x) = \sum_n \frac{N e^{-\mu} \mu^n}{\sqrt{2\pi} (\sigma_1) n!} \left(\exp \frac{(x - na)^2}{(\sigma_1 \sqrt{n})^2} \right) \quad (6.2)$$

where n is the number of photoelectrons (1-2 PEs are considered for the fit), N is a normalization constant, μ is the mean number of PEs, σ_1 is the single PE peak width, x is the charge in DUQ (Digital unit of charge), and a is the gain in DUQ per PE [86].

The timing of the PMT signals is used for position reconstruction and pulse discrimination (identifying abnormal events such as light noise). Time differences in each PMT channel can occur from slight variations in charge collection time within the PMT, signal propagation along the PMT cable, and the response time DAQ components. To compensate for these fluctuations relative time offsets (T0) corrections are measured

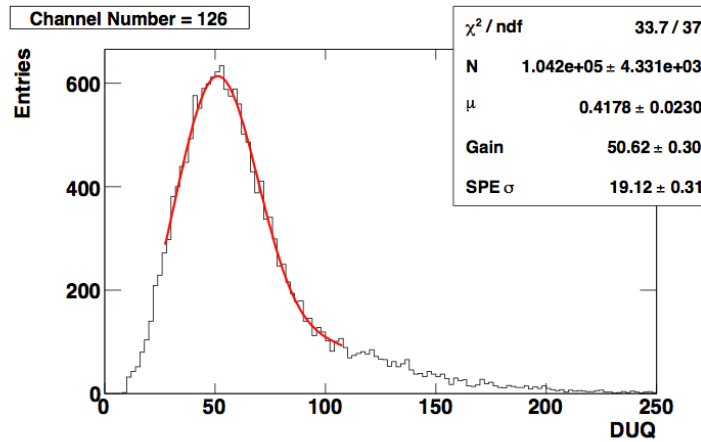


Figure 6.24: Charge distribution of a single PMT from IDLI calibration run [86]

with high intensity IDLI runs. The trigger time is recorded from the IDLI pulser. The time for the maximum amplitude of the PMT pulse is compared to the trigger of the IDLI.

Sets of target PMTs directly across from the light injection point are used to determine the base time. The fit to the maximum times are compared to the distance of the PMT from the IDLI injection point. The expected time from the base PMTs is compared to the observed times to find the relative time offset for each PMT (figure 6.25) [86]. The T0 values are then included in the charge and position reconstruction packages.

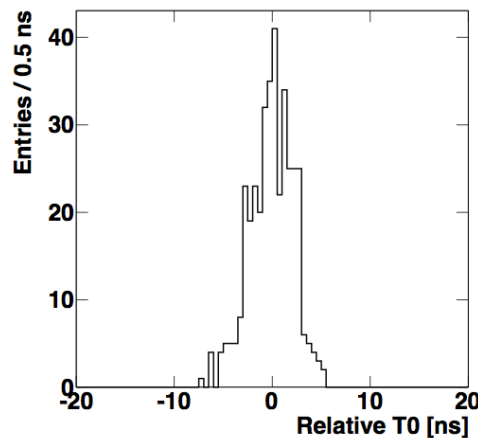


Figure 6.25: Distribution of PMT relative time offsets [86]

6.5.2 ^{252}Cf Source Deployment

Californium-252 is neutron source that is useful tool in determining the detector response and efficiency. An average of 3.77 neutrons are emitted by spontaneous fission of ^{252}Cf . Studies with neutron sources allow for a better understanding of the delay signal of inverse beta decay. Neutrons in the target will capture on H and Gd (capture on C can also occur but is a negligible effect). The capture on Gd is favored but a fraction will capture on H. The ratio of Gd to Gd + H captures can be extracted from the energy spectrum of ^{252}Cf deployments (figure 6.26). Fits are made for hydrogen capture ~ 2.2 MeV, Gd capture ~ 8 MeV, simultaneous Gd and H captures ~ 10 MeV, and two Gd captures ~ 16 MeV. The Gd/(Gd + H) ratio is 0.860 ± 0.005 for data and 0.880 ± 0.005 from MC [87].

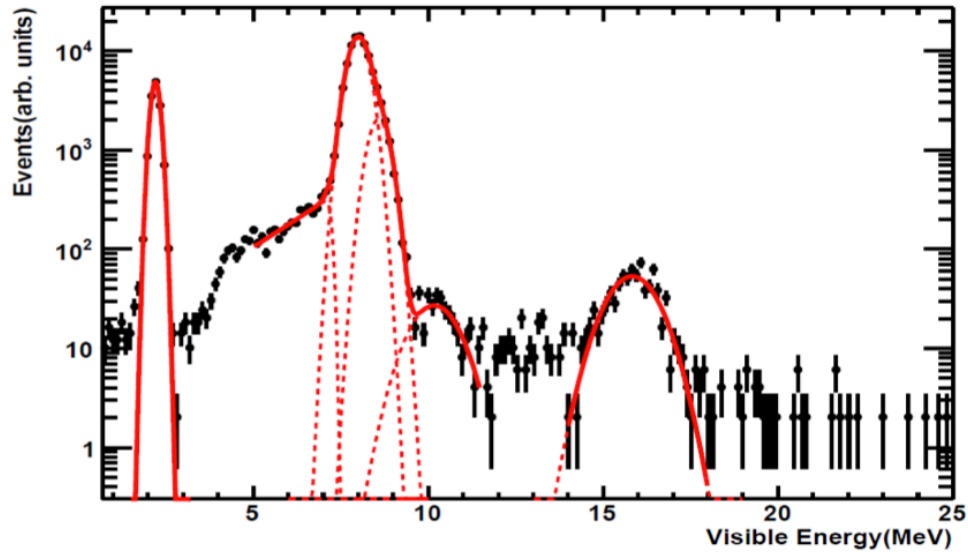


Figure 6.26: Energy spectrum of ^{252}Cf neutron capture [87]

6.5.3 Gamma Source Deployment

The deployment of various gamma sources can demonstrate the non-linearity response of the liquid scintillator and reveal discrepancies between data and MC models. Three gamma sources were deployed along the z-axis and in the GC guide tube, ^{60}Co (1.17 MeV + 1.33 MeV), ^{68}Ge (.511 + .511 MeV from β^+ annihilation) and ^{137}Cs (0.662 MeV). The energy peaks from the gamma sources at the center of the target, along with the gammas of neutron captures from ^{252}Cf , are used to determine the energy dependant correction to MC data (figure 6.27). Calibration runs taken with the Co and Cs sources along the central axis (Z) revealed a z-bias between data and MC (figure 6.27).

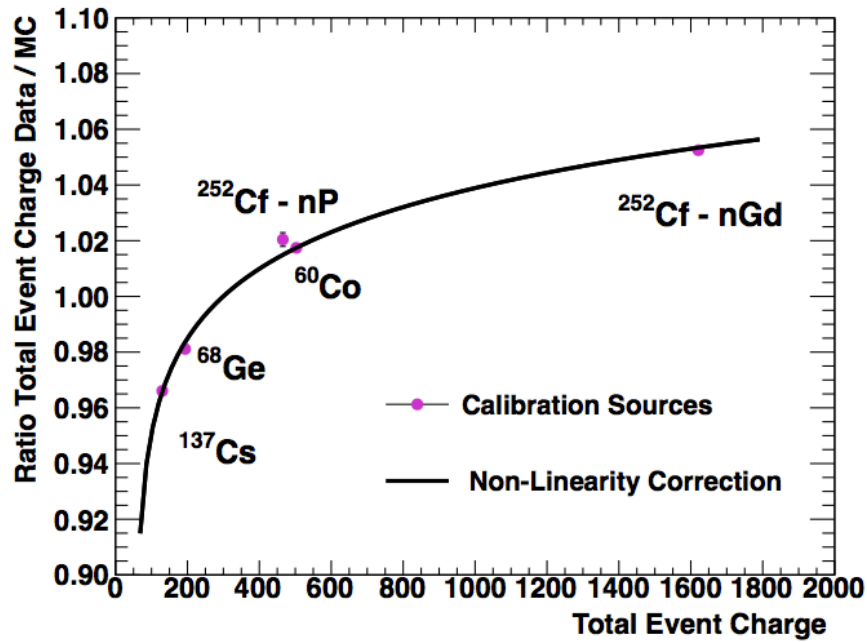


Figure 6.27: Ratio of data/MC for calibration source energy [88]

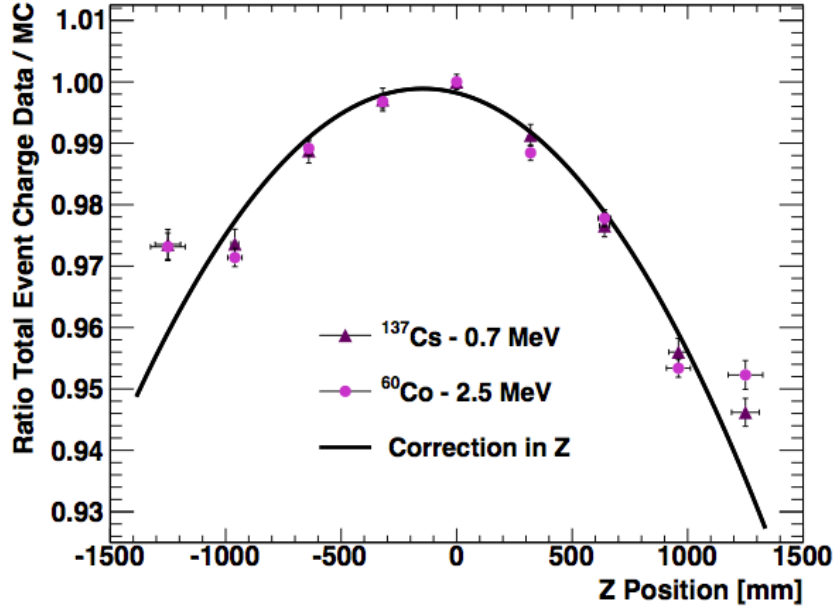


Figure 6.28: Ratio of data/MC for event charge verses z-position [88]

The complete correction function between data and MC is

$$PE_{\text{corr}} = PE_{\text{MC}} * f_E(PE_{\text{MC}}) * f_Z(Z_{\text{pos}}) \quad (6.3)$$

where PE_{MC} is the MC reconstructed number of photoelectrons, f_E is the energy dependant correction function,

$$f_E(PE_{\text{MC}}) = 0.0286966 * \log(PE_{\text{MC}} - 56.1478) + 0.842321 \quad (6.4)$$

and f_Z is the Z-position dependant correction function [88],

$$f_Z(Z_{\text{pos}}) = 0.998201 - 9.51483e^{-6} * Z_{\text{pos}} - 3.25985e^{-8} * (Z_{\text{pos}})^2 \quad (6.5)$$

Chapter 6.6

Spill In – Spill Out

The detector is designed to fully contain energy deposition for events that occur inside of the target volume. The gamma catcher allows for energy deposition of gammas produced in but exiting the target volume. Neutrons from IBD events can also cross the boundaries of the target and gamma catcher and must be accounted for. In an inverse beta decay event, the delay neutron can “walk” in the detector as undergoes collisions and thermalizes. Before being captured, the neutron typically travels ~ 30 cm. There is a chance for neutrons originating in one volume of the detector to travel into another volume before being captured. The spill-in effect is when neutrons originating in the gamma catcher which capture on Gd in the target volume. Spill-out is neutrons originating in the target travel into the GC before capture. Naively the spill in neutrons and spill out neutrons should cancel out. Due to the high cross-section for neutron capture on Gd present in the target, the spill-in effect is greater than spill-out. The consequences of this effect will be negligible for the two identical detector plan for Double Chooz. With only the far detector running for the first results from Double Chooz, the spill-in/spill-out effect must be taken into consideration. The effect has been examined using MC simulations to determine the increase in the number of neutron captures, or the spill-in current. The MC simulations examined both neutrino interactions and neutrons only the detector volumes.

The spill-in current, without taking IBD candidate criteria into consideration, is 6.46 ± 0.10 % [89]. The time between coincidence for prompt events and spill-in neutrons is longer due to the neutrons traveling in a medium free of Gd. The spill-in neutrons are also captured close to the acrylic boundary between the target and gamma catcher resulting in some loss of observable energy. These factors will reduce the spill-in events when the IBD candidate cuts are applied. The final spill-in current is found to be 1.37 ± 0.37 % [90].

Chapter 7

Analysis

Chapter 7.1

Inverse Beta Decay (IBD) Candidates

7.1.1 Event Selection Cuts

In order to extract IBD candidates a series of cuts is applied to reject events from the singles (described in Chapter 6.4). The cuts, based on the prompt-delay pairs expected for IBD are summarized in table 7.1.

Table 7.1: IBD Candidate Selection Cut Parameters.

Cut Description	Parameters
Muon Veto – events following a muon	1 ms veto after Charge in IV > 10,000 DUQ or Energy in ID > 30 MeV
Prompt and Delay – no activity in IV	Charge in IV < 10,000 DUQ
Prompt and Delay – trigger condition	Not an external trigger
Prompt – light noise rejection	$Q_{\max}/Q_{\text{tot}}$ ratio ≤ 0.09 and T_{start} RMS ≤ 40 ns
Prompt – energy range	$0.7 \text{ MeV} \leq \text{Energy in ID} \leq 12 \text{ MeV}$
Delay – light noise rejection	$Q_{\max}/Q_{\text{tot}}$ ratio ≤ 0.06 and T_{start} RMS ≤ 40 ns
Delay – energy range	$6 \text{ MeV} \leq \text{Energy in ID} \leq 12 \text{ MeV}$
Time delay – between prompt and delay	$2 \mu\text{s} < \Delta t < 100 \mu\text{s}$
Isolation Cuts	No events 100 μs preceding prompt Only one delay 2 – 100 μs after prompt No events 100 – 400 μs following prompt

The light noise cuts were discussed in chapter 6.2 and introduces a negligible inefficiency as compared to MC simulations. These cuts have been successful in limiting the impact on the data quality. Studies continue into the nature of the light noise to determine if additional cuts are needed.

As mentioned a 1ms veto is applied after a muon event. The definition of a muon event is either criteria of 10,000 DUQ (digital units of charge collected by FADC) in the IV or 30 MeV in the ID. The inner detector condition was included for muons entering the inner volume without a signal in the IV. This condition introduces a dead time equal to the number of muons times 1ms. This reduces the total analyzed run time by 4.7 days leaving a live time of 96.8 days (figure 7.1). A correction factor of 0.9547 is applied to MC data.

The external trigger cut is to ensure the trigger was from a physics event and not an external trigger used for system monitoring. The prompt energy range, between 0.7 MeV to 12 MeV, is wide enough to contain events at the IBD threshold and the tail of the IBD energy spectrum. The delay energy range, 6 MeV to 12 MeV, can introduce some inefficiency. To quantify this systematic the ^{252}Cf calibration data and ^{252}Cf MC was used. The spontaneous fission of ^{252}Cf can produce gamma ray in addition to the neutrons emitted [91]. The gamma rays followed by neutron captures can be used as prompt-delay pairs. By comparing a 6-12 MeV delay energy cut with a 4-12 MeV delay energy cut for the efficiency can be determined. The efficiency is calculated as the ratio of events in the 6-12 MeV range to events in the 4-12 MeV range. The ratio for calibration data is 94.40% and for MC 93.91% [92]. The result is a 0.6% systematic uncertainty.

The time coincidence cut applied is 2-100 μs between prompt and delay events. Similar procedures to the neutron capture energy window are followed using ^{252}Cf data and MC. A ratio of the number of events in the time window of 2-100 μs to the events in the time window 0-200 μs is determined. A 0.5% systematic uncertainty was found for the delta-t cut.

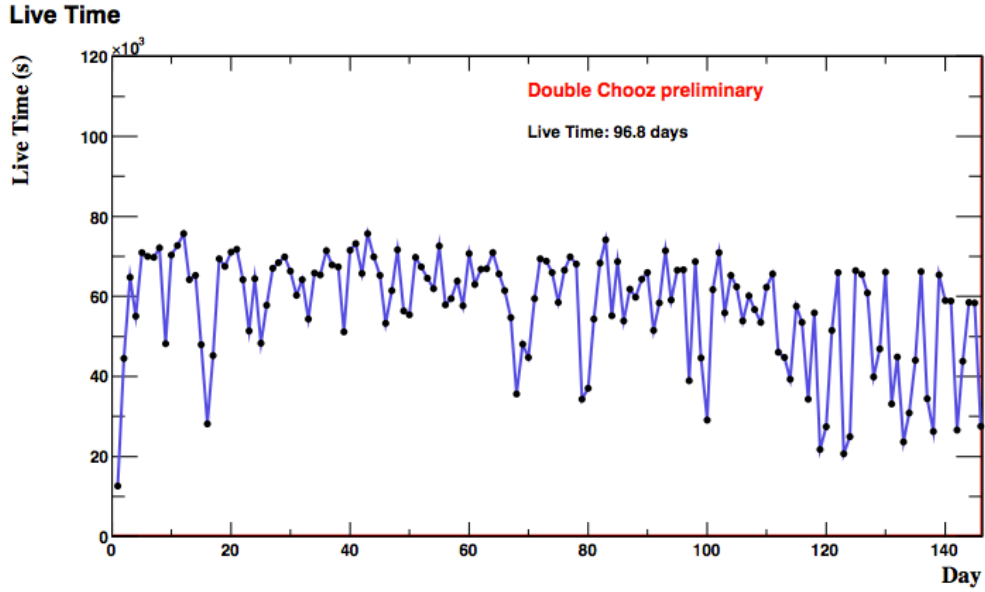


Figure 7.1: Live time per day for DC first data set.

The isolation cut was implemented to remove signs of multiple neutron coincidence (figure 7.2). This occurs as multiple neutrons from untagged mouns capture on H in the gamma catcher or Gd in the target. The vetoed time requires a 0.995 correction factor for MC.

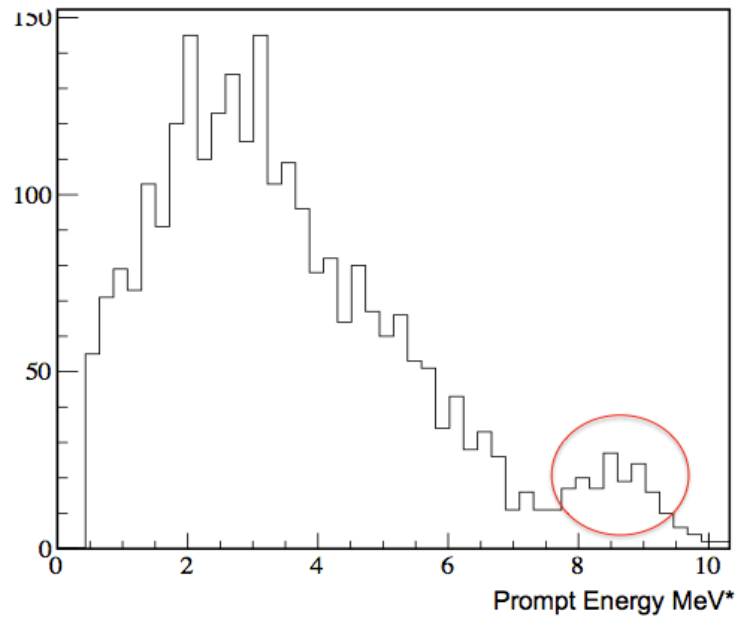


Figure 7.2: Prompt energy spectrum with multiple neutron peak

7.1.2 Candidates

Will all selection cuts applied 4121 candidate events remain. This gives a neutrino rate of 42.6 neutrino events per day (figure 7.3). The delay energy spectrum is shown in figure 7.4. There are some energy scale corrections that remain under investigation. The peak-reconstructed energy can be used to check the stability of the light yield of the scintillator (figure 7.5).

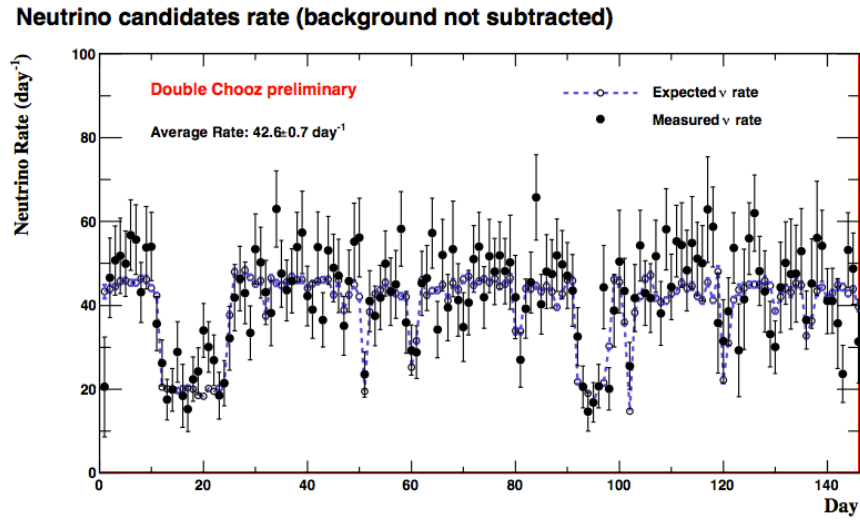


Figure 7.3: Daily neutrino candidate rate

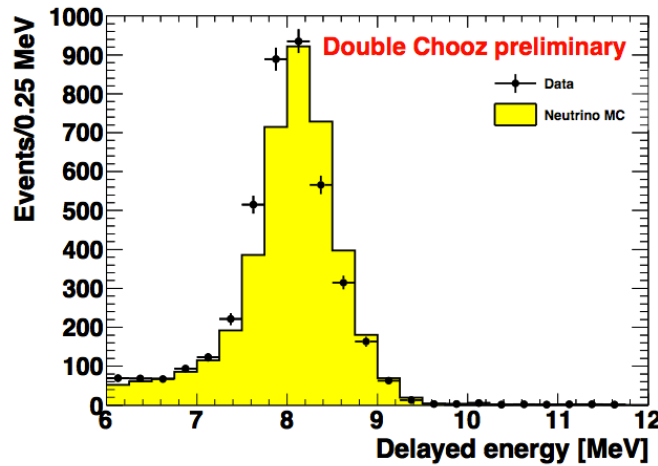


Figure 7.4: Delay energy spectrum for IBD candidates. Black points are data and yellow is MC.

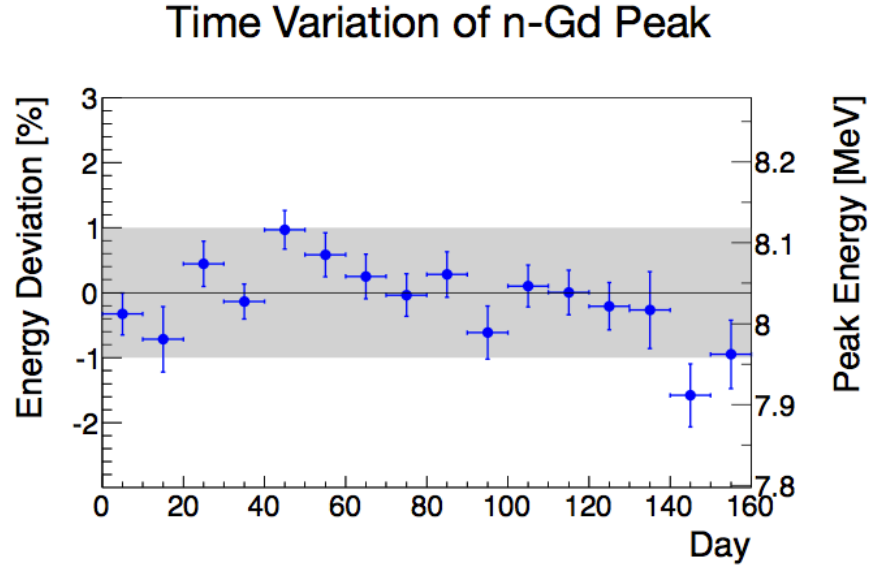


Figure 7.5: Stability plot of light yield of Double Chooz Liquid Scintillator from peak energy of neutron capture on Gd.

The position reconstruction of candidate events shows that events are well contained within the target volume (figures 7.6-7.7). No spatial cuts were used in candidate extraction.

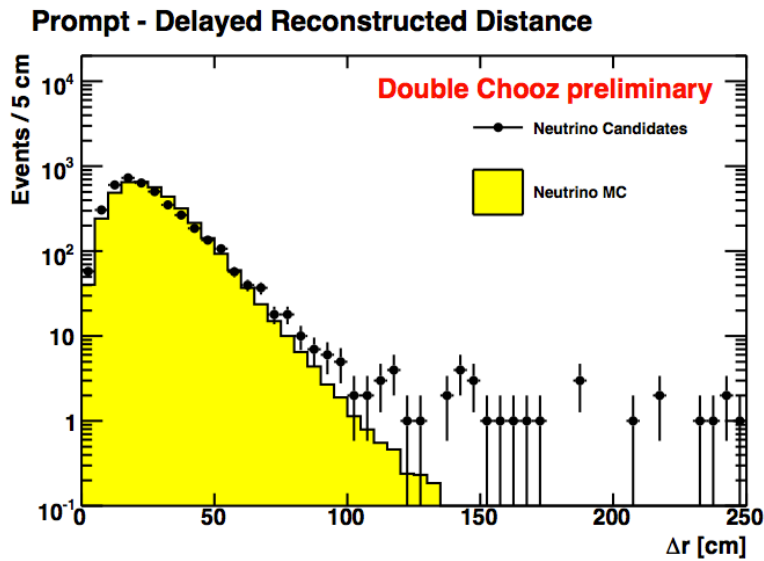


Figure 7.6: Distribution of distance between prompt-delay vertices.

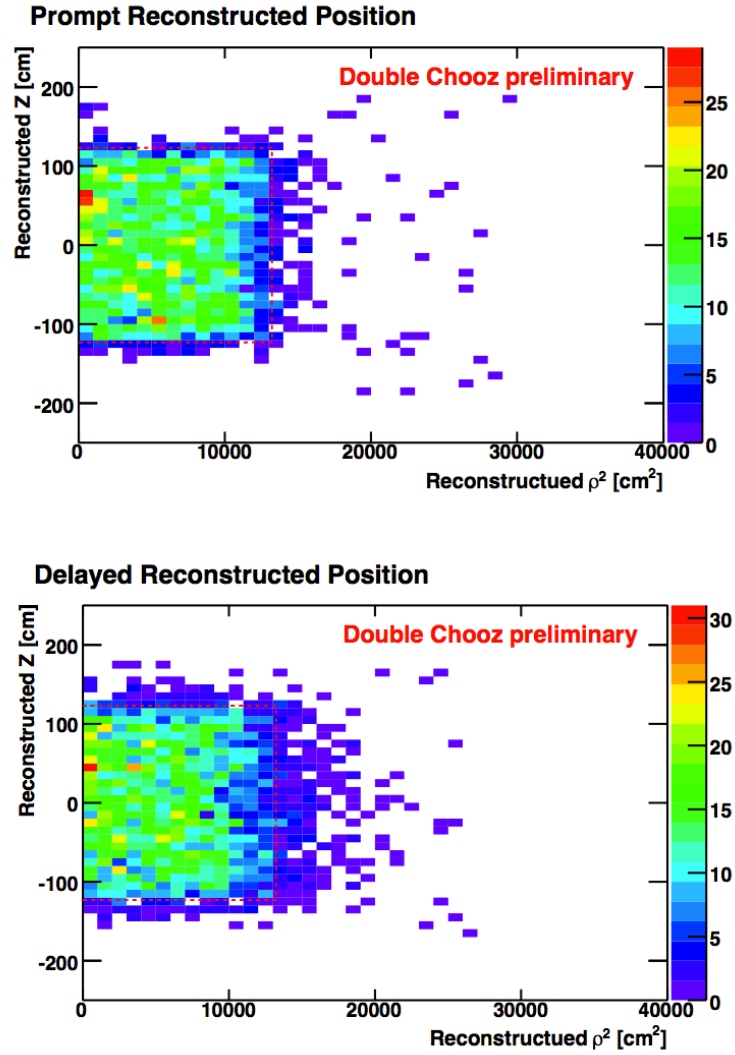


Figure 7.7: Distribution of reconstructed vertex z verses ρ^2 (dashed red line is target volume.
Upper – prompt events, Lower – delay events.

Chapter 7.2

Backgrounds

7.2.1 Accidental background

The accidental backgrounds from radioactive isotopes could be estimated from the singles rates for the prompt and delay energy windows. As discussed in chapter 6.4,

the estimated rate is 0.48 day^{-1} . Since the accidental background is uncorrelated using an off-time window can do the determination of the rate. The off time window allows a probe of the accidental rate absent of IBD events or other correlated backgrounds. The search criteria (prompt energy, delay energy, light noise cuts, etc.) is the same for IBD event extractions. Instead of a 2-100 μs window we used a 98 μs window that begins 1.002 ms after the prompt and isolation cut on the delay window. Because of the low accidental rate 198 consecutive windows are used. This will provide sufficient statistics for both the rate and prompt energy shape of the accidental backgrounds. The shape is expected to be similar to that of the singles energy spectrum in figure 6.13. The off-window will also have to meet moun veto and isolation conditions. The muon veto will ensure that events following muons will not be included in the accidental counts. The isolation condition on the delay is similar to the prompt conditions, no events -100 μs before the window or +400 μs after the window. The delay isolation condition ensured that no IBD, correlated background or multiple neutrons were counted. A total of 6339 accidental events were observed. With a factor of 1/198 the accidental rate is $0.332 \pm 0.004 \text{ (stat) day}^{-1}$. The spectrum was the same as the singles spectrum (figure 7.8).

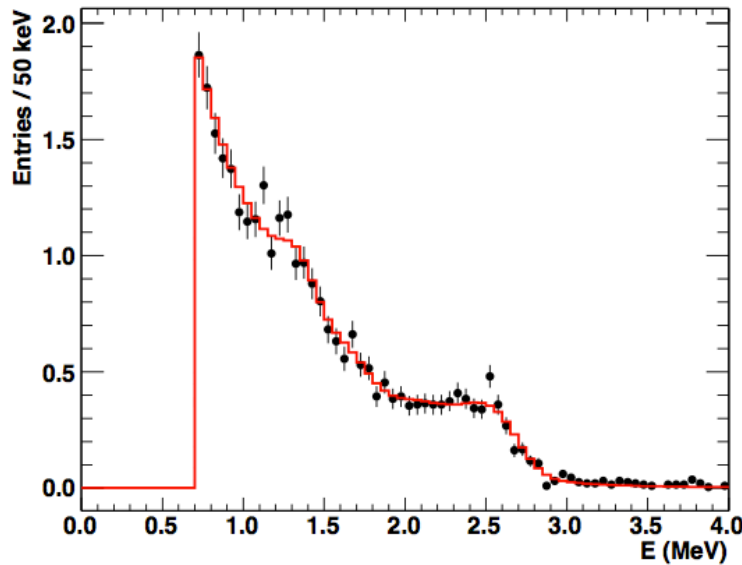


Figure 7.8: Scaled accidental prompt spectrum (Black points are data, Red line is scaled singles rate).

7.2.2 ^9Li background

^9Li is the first of two correlated background induced by muons. The β -n decay, occurring $\sim 50\%$ of ^9Li decays, will mimic the IBD prompt and delay pairs. A scheme to differentiate ^9Li events from IBD events is needed to determine the rate of this background. There are 5 branches of ^9Li that are followed by neutron emission. From the beta spectra of these branches the overall prompt signal energy spectrum can be modeled (figure 7.9). Following the method in KamLAND [93], the higher energy tail of the ^9Li beta spectrum was examined. In order to be above the IBD energy spectrum the prompt energy window was 9-14 MeV was used. All other search criteria were the same as IBD. In this data set the statistics were too low for conclusive results.

The half life of ^9Li is 178 ms which is correlated with the high-energy muon producing the isotope, whereas no correlation should exist between muon and IBD. A plot of the time since last muon and prompt candidates have two features, flat for IBD and an exponential for ^9Li . The time distribution plot between all tagged muons and prompt candidates is saturated with IBD events and the exponential feature is hidden (figure 7.10). Because the only showering muons reaching the inner volume will produce ^9Li , further constraints were placed on the muon selection. The time between muon and prompt events was limited to muons with energy deposits between 200-700 MeV (figure 7.11 and 7.12). The energy constraints of 200-700 MeV deposited in the inner detector allow for determination of showering muon events and allow for the separation of ^9Li events. With these conditions the exponential feature could be seen. Based on the number of events above the flat fit the number of ^9Li events were extracted. A conservative rate of $2.3 \pm 1.2 \text{ day}^{-1}$ is used. The beta spectrum is normalized to the rate to give for the estimated background shape (figure 7.13).

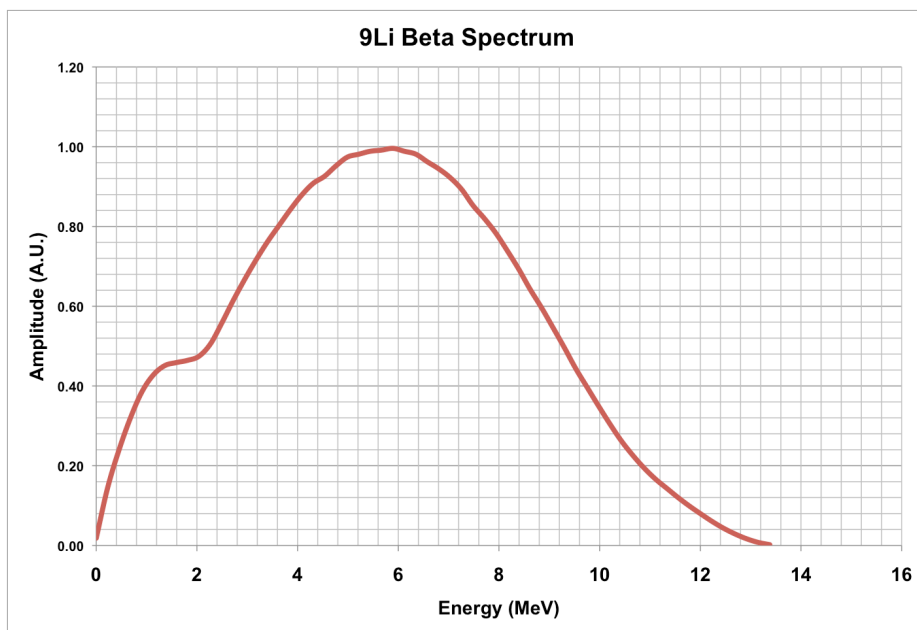


Figure 7.9: Calculated energy spectrum of ^9Li beta decays.

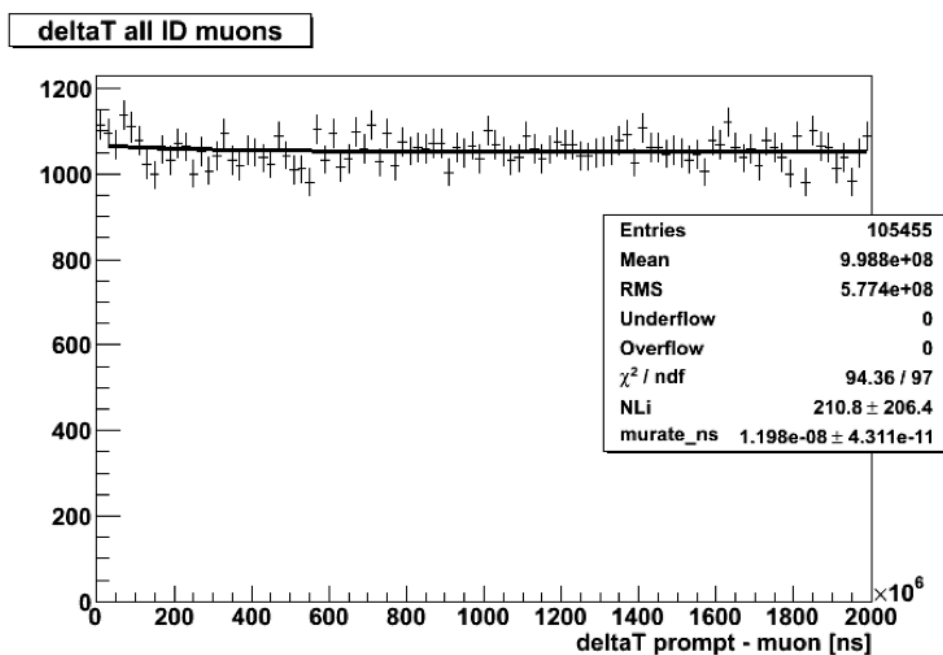


Figure 7.10: Time distribution to between muons and prompt events.

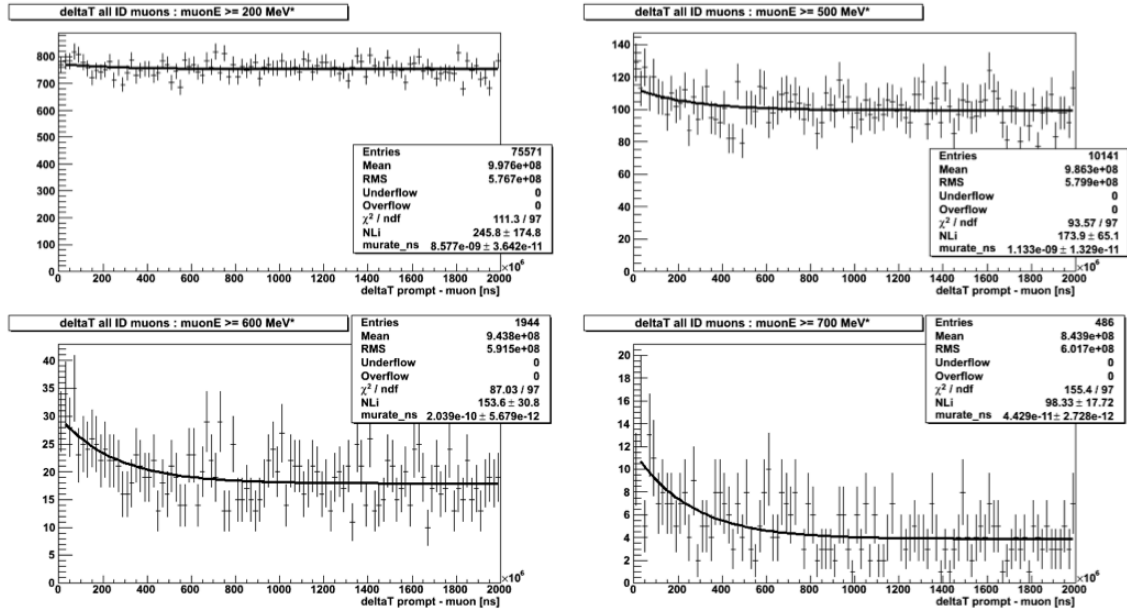


Figure 7.11: Delta-t muon to prompt event for: Upper left muons $>200\text{MeV}$, Upper right $>500\text{MeV}$
Lower left $>600\text{MeV}$ and lower right $>700\text{MeV}$

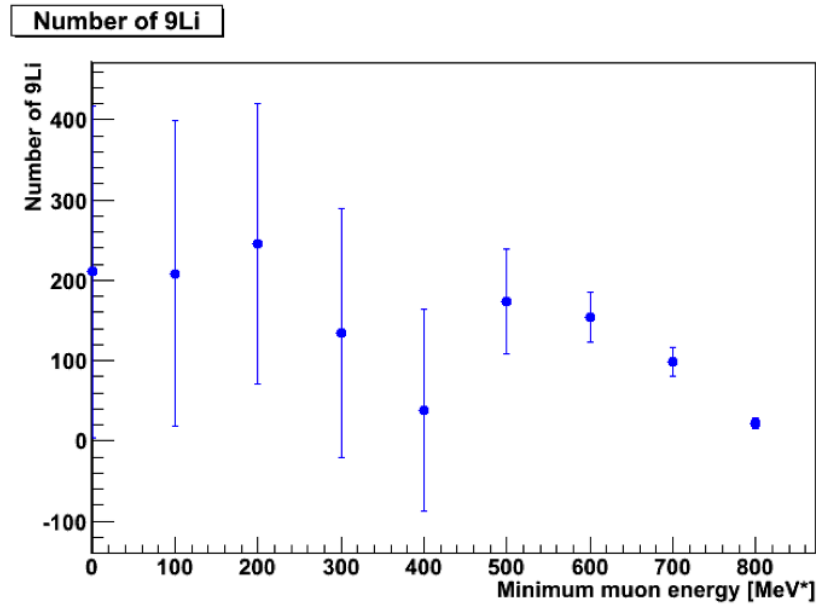


Figure 7.12: Summary of 9Li events for muon energy cuts.

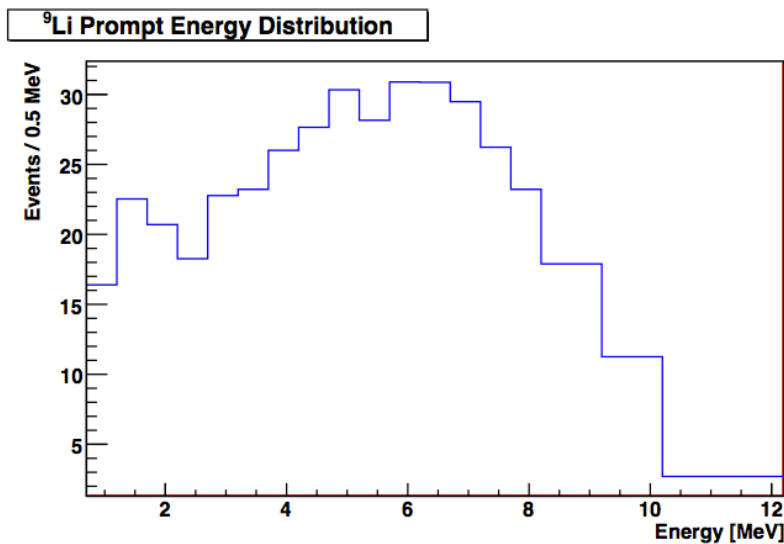


Figure 7.13: Energy spectrum of ^9Li used for this analysis.

7.2.3 Fast Neutron Background

Fast Neutrons produced by untagged muons can give prompt-delay pairs from the recoil of a proton followed by neutron thermalization and capture on Gd. The original CHOOZ experiment accumulated large data sets with both reactors off to analyze the background rates. The CHOOZ rate for fast neutrons was $1.01 \pm 0.04 \pm 0.1 \text{ day}^{-1}$ [51]. Fast neutrons have a relatively flat energy spectrum that can span up to tens of MeV. For a sample consisting primarily of fast neutrons a prompt window of 12-30 MeV was used (figure 7.14). Events originating around the chimney from untagged stopped muons were also in the high-energy range. Using a volume cut around the chimney the stopping muon events removed from the fast neutron analysis. The rate in the high energy range then extrapolated back to the prompt candidate energy range giving a rate of $0.7 \pm 0.5 \text{ day}^{-1}$ (figure 7.15). [94]

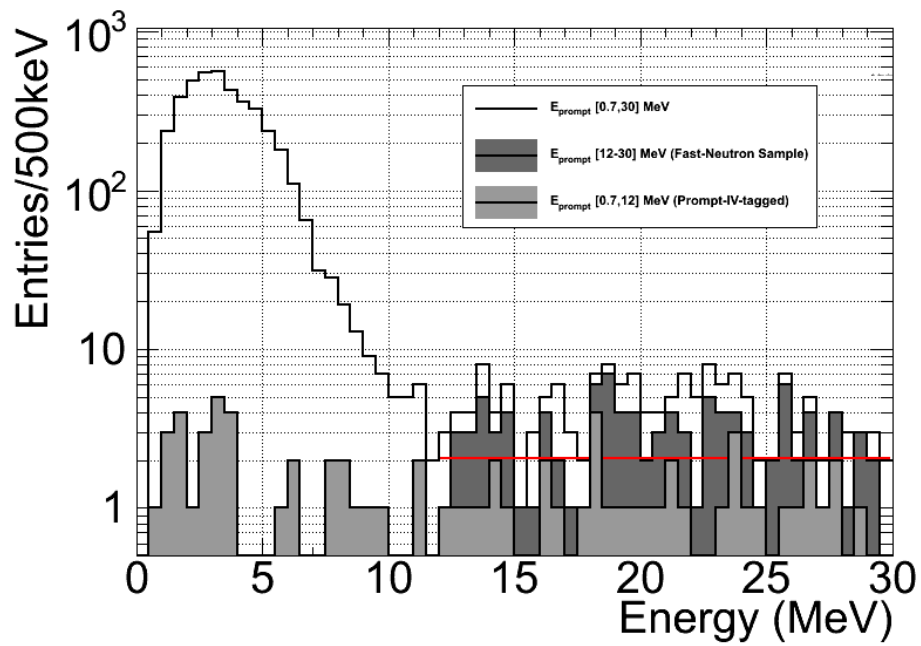


Figure 7.14: Energy spectrum up to high energy prompt events for fast neutron analysis [94]

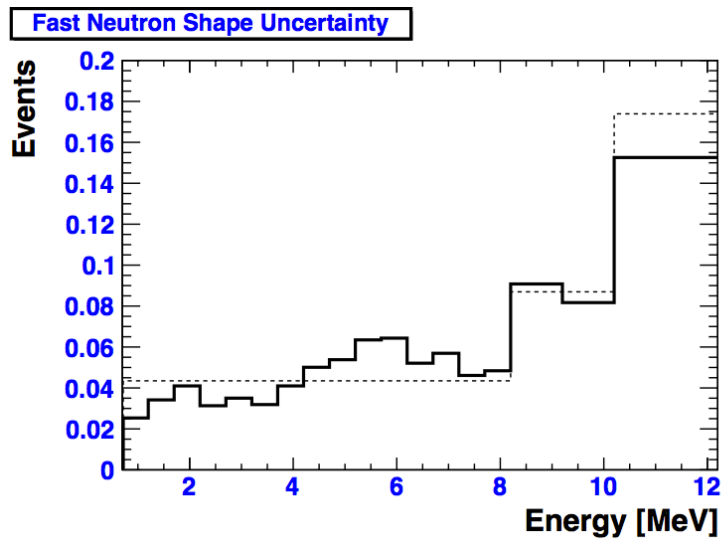


Figure 7.15: Fast Neutron Energy spectrum extrapolated to IBD prompt window [94]

Table 7.2: Summary of Backgrounds.

Source	Rate (day^{-1})
Accidental	0.332 ± 0.004
^9Li	2.3 ± 1.2
Fast Neutrons	0.7 ± 0.5
Total	3.46 ± 1.26

Chapter 7.3

Two Reactors Off Background Data

The total background rate of $3.46 \pm 1.26 \text{ day}^{-1}$ (which is a signal to background ratio of $\sim 12:1$) was validated during a day of data with both Chooz reactors off. 22 hours of background runs were taken during the off-off time. Two events were recorded meeting the IBD candidate criteria each having the characteristics of ^9Li decay. The prompt energies of the two events were 9.8 MeV and 4.8 MeV with time since last high-energy muon of 200ms and 241ms respectively. The two events background events are consistent with the estimations of the backgrounds.

Chapter 7.4

Reference Neutrino Spectrum

For a comparison to the IBD candidates the expected spectrum is generated using a MC framework called DCRxtrTools. Reactor inputs (thermal power, reactor core composition, cross-sections, etc) described in chapter 5 are used for event generation. Specific data run times are used to with the reactor inputs to determine the energy-binned flux. The sensitivity of the calculation is dominated by the cross-section per fission term (equation 5.8), which relies on the knowledge of the flux spectrum (equation 5.1). To suppress this uncertainty an “anchor point” from the Bugey experiment is utilized.

Bugey-4 was a short baseline (15m) reactor experiment [95]. The precision that was measured of an unoscillated reactor anti-neutrino spectrum can be used as a virtual near detector for the Double Chooz far detector. The mean cross-section per fission becomes

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_l (\alpha_l - \alpha_l^{Bugey}) \langle \sigma_f \rangle_l \quad (7.1)$$

The expected neutrino events are stored in a root file with the referenced data run number. In addition to the expected neutrino events the uncertainty contributions are stored to construct the detector covariance matrix [75].

Chapter 7.5

θ_{13} Analysis

Multiple approaches were performed for an oscillation hypothesis for reactor anti-neutrinos. The goal is to extract the theta-13 parameter of PMNS matrix. A deficit from the expected number of anti-neutrinos to the number detected would imply a non-zero contribution of the term $\sin^2(2\theta_{13})$ in the survival probability (Equation 2.18). Any approach used must include the systematic uncertainties described in previous chapters. The systematic uncertainties are summarized in table 7.2.

Table 7.3: Systematic Uncertainties for Double Chooz first phase [96].

Detector		Reactor		Backgrounds	
Energy Response	1.74%	Thermal Power	0.46%	Accidental	0.071%
E _{del} Containment	0.6%	Fuel Composition	0.87%	⁹ Li	2.82%
Gd/H Ratio	0.58%	Energy per Fission	0.16%	Fast Neutrons	0.909%
Delta-T	0.5%	Reference Spectrum	0.5%		
Spill in/Spill out	0.37%	IBD Cross-section	0.2%		
Trig. Efficiency	0.4%	Bugey 4 Anchor Point	1.42%		
Target Protons	0.3%	Baseline	0.2%		
Total	2.1%	Total	1.8%		

A simple approach is to look only at the ratio of the rates for observed and expected.

$$R = (N_{\text{obs}} - N_{\text{bkg}})/N_{\text{pred}} \quad (7.2)$$

The number observed, N_{obs} , was 4121 ± 64.20 (stat) which includes background. The number for the three contributing backgrounds are given in Chapter 7.2. The predicted rate, as calculated by DCRxtrTools, was from a 100 times statistics with no oscillations included. The resulting predicted rate is 4344 ± 165 (syst) with backgrounds added. The resulting ratio for the first 101 days of data from Double Chooz is 0.944 ± 0.16 (stat) ± 0.040 (syst). Based on the variations in the thermal power of each reactor during the DC first data set, the number of expected rates verses the observed rates is plotted (figure 7.16). Each data point represents the total thermal power of the reactors. To determine a value for $\sin^2(2\theta_{13})$ two different χ^2 statistical goodness of fit approaches are used.

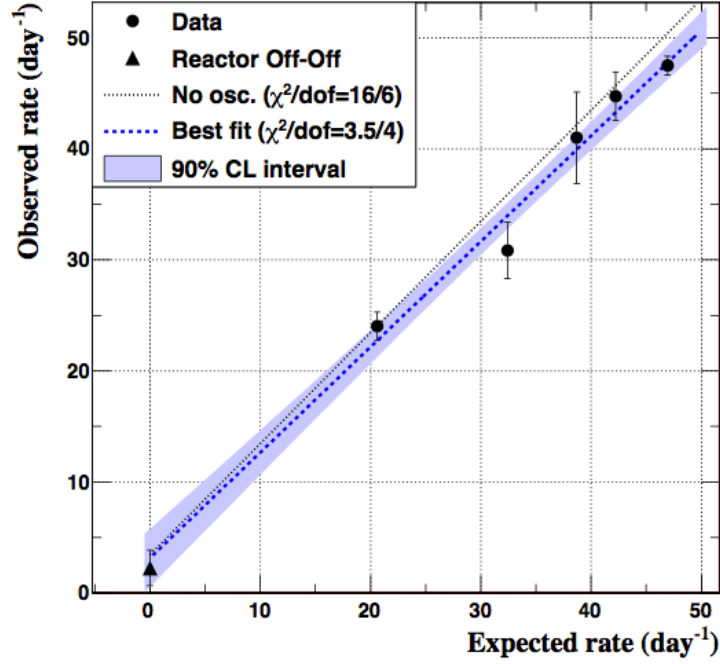


Figure 7.16: Observed verses Expected anti-neutrino rate. Data points are for various thermal power levels of the reactors [96]

7.5.1 Covariance Matrix χ^2 Analysis

The covariance matrix approach for the goodness-of-fit incorporates the determined uncertainties into error matrices. The basic form of the χ^2 fit is

$$\chi^2 = \sum_{ij} \left(N_i^{obs} - N_i^{pred} \right) \times M_{ij}^{-1} \left(N_j^{obs} - N_j^{pred} \right) \quad (7.3)$$

Where i and j are the energy bins for the prompt energy spectrum of the data and MC sets. The binning for Double Chooz analysis is 0.5 MeV bins from 0.7-8.2 MeV, 1.0 MeV bins from 8.2-10.2 MeV, and 2.0 MeV from 10.2-12.2 MeV. N^{obs} is the number of prompt events in the respective i and j bins. N^{pred} is the number is a combination of the

number of MC neutrino events from each reactor ($R = 1,2$) and the estimated backgrounds ($b = \text{accidental, } ^9\text{Li, Fast neutron}$).

$$N_{i(j)}^{pred} = \sum_R N_{i(j)}^{\nu R} + \sum_b N_{i(j)}^b \quad (7.4)$$

The matrix M_{ij} is the covariance matrix. This matrix can be represented as the sum of uncorrelated matrices.

$$M_{ij} = M_{ij}^{\text{Reactor}} + M_{ij}^{\text{Detector}} + M_{ij}^{\text{stat}} + \sum_b M_{ij}^b \quad (7.5)$$

Each matrix is a representative of the uncertainties arising from the sources labeled (Reactor, Detector, Statistical, and background) [97]. The full χ^2 equation is

$$\begin{aligned} \chi^2 = & \sum_{ij} \left(N_i^{obs} - \sum_R N_i^{\nu R} + \sum_b N_i^b \right) \\ & \times \left(M_{ij}^{\text{Reactor}} + M_{ij}^{\text{Detector}} + M_{ij}^{\text{stat}} + \sum_b M_{ij}^b \right)^{-1} \\ & \times \left(N_j^{obs} - \sum_R N_j^{\nu R} + \sum_b N_j^b \right) \end{aligned} \quad (7.6)$$

Similar to the total covariance matrix, the reactor matrix (M^{Reactor}) consists of several components that contribute to the uncertainty.

$$M_{ij}^{\text{Reactor}} = M_{ij}^{Np} + M_{ij}^{\varepsilon} + M_{ij}^{\sigma Bugey} + M_{ij}^{x \text{ sec}} + \sum_R \left(M_{ij}^{\alpha R} + M_{ij}^{LR} + M_{ij}^{PR} \right) \quad (7.7)$$

Where N_p – number of protons, ε - detector efficiency, σ_{Bugey} – Bugey 4 anchor point, x_{sec} – IBD cross section, α - reactor core components, L – distance to reactor, P – thermal power. The terms of the matrices for each parameter are found using Jacobian formalizim [75].

$$M_{ij}^{\text{Param}} = \frac{\partial N_i^{\text{exp}}}{\partial(\text{Param})} (\sigma_{\text{Param}})^2 \frac{\partial N_j^{\text{exp}}}{\partial(\text{Param})} \quad (7.8)$$

where N^{exp} is the expected number of events in energy bin i and σ_{param} is the uncertainty of the parameter.

The detector matrix (M^{Detector}) is based in the correction functions between data and MC described in Chapter 6.5.2. From the correction functions a parameter (6x6) matrix is formed. The covariance matrix is then constructed using a MultiSim approach. Random parameter components are drawn from the parameter matrix to create many MC data sets. From the normal IBD criteria candidates are extracted and the prompt energy spectrum is saved. The matrix elements are then determined from

$$M_{ij}^{\text{Detector}} = \frac{1}{\# \text{MC runs}} \sum_n \left(p_i^n - p_i^{\text{def}} \right) \left(p_j^n - p_j^{\text{def}} \right) \quad (7.9)$$

Where n is summed over the number of MC runs taken (590 for the DC first results), p^n is the value for the i or j bin for the single run n , and p^{def} is the value for the default parameters.

The statistical matrix (M^{stat}) is a diagonal matrix containing the number of events in each energy bin i ,

$$M_{ii} = N_i \quad (7.10)$$

The three background matrices are constructed from the rates, energy spectrum and uncertainties described in chapter 7.2.

With all elements, the extracted candidates, MC expected rates, background estimates (figure 7.17) and matrices, the probability of electron neutrino survival is introduced into the χ^2 function. It is minimized to the best fit for $\sin^2(2\theta_{13})$ (figure 7.18). The best fit to the rate and shape analysis is $\sin^2(2\theta_{13}) = 0.0856 \pm 0.041$ (stat) ± 0.030 (syst). For a rate only analysis the best fit is $\sin^2(2\theta_{13}) = 0.1044 \pm 0.030$ (stat) ± 0.076 (syst).

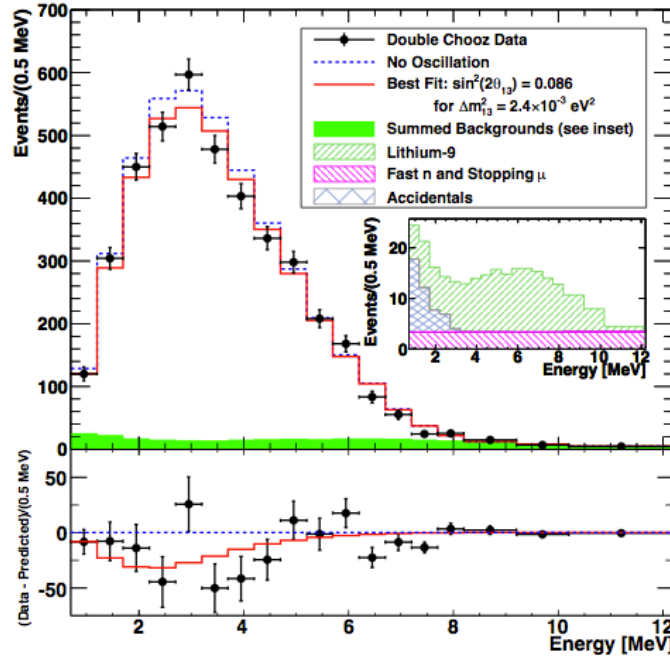


Figure 7.17: The prompt energy spectrum of data, backgrounds, MC for no oscillation and best fit [96]

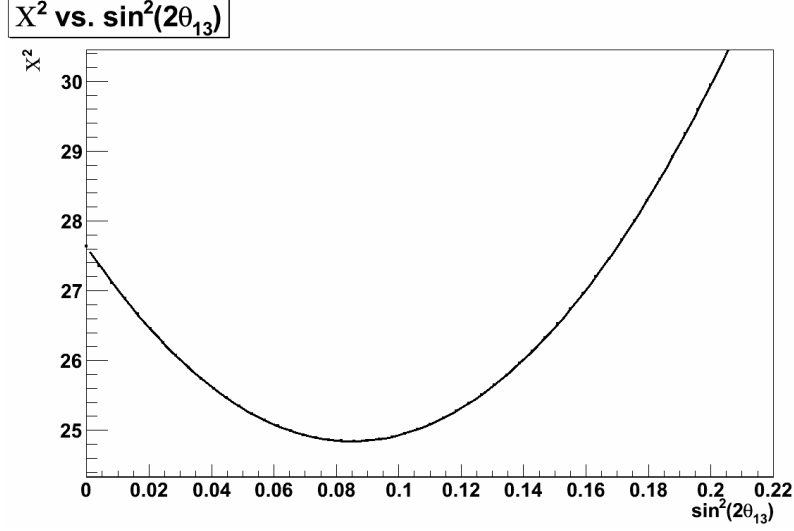


Figure 7.18: χ^2 vs $\sin^2(2\theta_{13})$ distribution. For $\Delta m^2_{13} = 2.4 \times 10^{-3} \text{ eV}^2$, 17 degrees of freedom [97]

7.5.2 Background Pulls χ^2 Analysis

The Pulls approach to the final fit analysis is similar to the Covariance Matrix approach in that the error matrices are still employed. In this approach two of the backgrounds (9Li and fast neutrons) and the energy scale are “pull” terms that are allowed to vary along with the value for $\sin^2(2\theta_{13})$ [97]. The χ^2 terms are modified to

$$\begin{aligned}
 \chi^2 = & \sum_{ij} \left(N_i^{obs} - \left(\sum_R N_i^{vR} + \sum_b N_i^b(P_b) \right) \right) \times \left(M_{ij}^{Reactor} + M_{ij}^{stat} \right)^{-1} \\
 & \times \left(N_j^{obs} - \left(\sum_R N_j^{vR} + \sum_b N_j^b(P_b) \right) \right) + \sum_b \frac{(P_b)^2}{\sigma_b^2} \\
 & + (P_\alpha - P_\alpha^{CV})(M_{\alpha\beta}^{Detector})^{-1}(P_\beta - P_\beta^{CV})
 \end{aligned} \tag{7.11}$$

Table 7.4: Pull term corrections for the correlated backgrounds and energy scale [96]

	Fast n. Bkg(%)	^9Li (%)	EScale (value)
Rate only	100 (46)	100 (52)	0.997 (0.007)
Rate + Shape	95.2 (38)	81.5 (25.5)	0.998 (0.005)

where P_b are correction terms for the backgrounds. The $M_{\alpha\beta}$ matrix is the 6x6 parameter matrix based on energy scale corrections. P_α is the correction term for the energy scale matrix. The results for the backgrounds and energy scale correction are given in table 7.3. New constraints are put on the ^9Li down to $1.9 \pm 0.5 \text{ day}^{-1}$ and on the correlated background down to $0.8 \pm 0.3 \text{ day}^{-1}$. The best fit results for $\sin^2(2\theta_{13})$ from the pulls approach are $0.1044 \pm 0.030 \text{ (stat)} \pm 0.076 \text{ (syst)}$ for rate only and $0.086 \pm 0.041 \text{ (stat)} \pm 0.030 \text{ (syst)}$ for rate and shape analysis [96].

7.5.3 90% Confidence Level

In order to determine the 90% CL range for Double Chooz results a frequentist study was performed. For this method thousands of “toy” models are made for differing $\sin^2(2\theta_{13})$ values. For each $\sin^2(2\theta_{13})$ value the MC set is built by taking random draws for the covariance matrices. In each model a $\Delta\chi^2$, equation 7.12, is calculated.

$$\Delta\chi^2 = \chi^2(\sin^2(2\theta_{13})^{\text{theory}}) - \chi^2(\sin^2(2\theta_{13})^{\text{bestfit}}) \quad (7.12)$$

Boundaries are found for the best 90% of the fake experiments and their corresponding best fit values. The Feldman-Cousins belt (figure 7.19) gives the 90% CL belt which is compared with the best fit value of the data [97]. The allowed region for the Double Chooz first data set is $0.017 < \sin^2(2\theta_{13}) < 0.16$ at 90% CL.

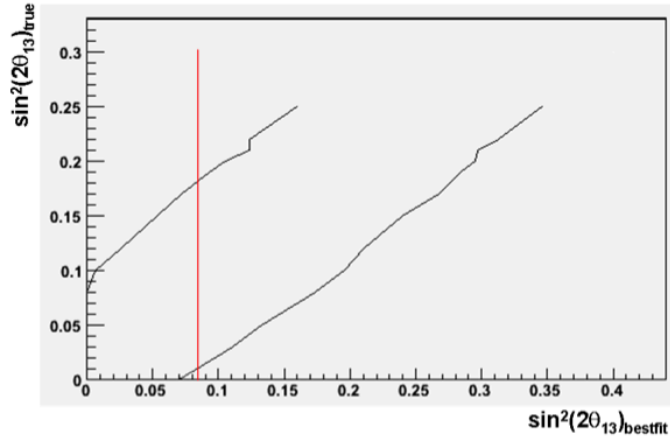


Figure 7.19: 90% CL belt from frequentist study [97] The black lines are the boundaries of the best 90% of MC experiments. Y-axis is the $\sin^2(2\theta_{13})$ value used for the MC, X-axis is the best fit value for $\sin^2(2\theta_{13})$, and the red line is the best fit value from DC analysis.

Chapter 7.6

Impact on Future Experiments

A measurement of the last neutrino mixing angle, θ_{13} , is an important step toward a more complete understanding of neutrino physics. The measurement of θ_{13} from reactor sources produces a result only dependant on the distance (L), neutrino energy (E) and Δm^2_{23} (which has been precisely measured from accelerator and atmospheric experiments). A search for the θ_{13} parameter can also performed with accelerator experiments by looking at the appearance probability of electron neutrinos from a muon neutrino beam. For this case the full three-flavor probability is

$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \left(\Delta m_{31}^2 \frac{L}{4E} - aL \right)}{\left(\Delta m_{31}^2 \frac{L}{4E} - aL \right)^2} \left(\Delta m_{31}^2 \frac{L}{4E} \right)^2 \\
& + \cos \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos \left(\Delta m_{32}^2 \frac{L}{4E} \right) \cdot \\
& \left(\frac{\sin \left(\Delta m_{31}^2 \frac{L}{4E} \mp aL \right)}{\Delta m_{31}^2 \frac{L}{4E} \mp aL} \left(\Delta m_{31}^2 \frac{L}{4E} \right) \right) \left(\frac{\sin aL}{aL} \Delta m_{21}^2 \frac{L}{4E} \right) \\
& + \sin \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin \left(\Delta m_{32}^2 \frac{L}{4E} \right) \cdot \\
& \left(\frac{\sin \left(\Delta m_{31}^2 \frac{L}{4E} \mp aL \right)}{\Delta m_{31}^2 \frac{L}{4E} \mp aL} \left(\Delta m_{31}^2 \frac{L}{4E} \right) \right) \left(\frac{\sin aL}{aL} \Delta m_{21}^2 \frac{L}{4E} \right) \\
& + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 aL}{(aL)^2} \left(\Delta m_{21}^2 \frac{L}{4E} \right)^2
\end{aligned} \tag{7.13}$$

where δ is the CP-violating phase and $a = G_F N_e / \sqrt{2}$ from the matter effects of the beamline through the Earth. The full term involves both solar atmospheric and θ_{13} dependencies. With relatively large value of θ_{13} , the chance to probe the other oscillation parameters, δ_{cp} phase and the sign of Δm_{31}^2 , is possible with accelerator beam experiments. Two long baseline experiments looking for electron neutrino appearance are already underway. MINOS [98] (FermiLab to Soudan) and T2K [99] (J-PARC to Kamiokande) have baselines of 735km and 295km respectively. NOvA (FermiLab to Ash River, Minnesota) with a baseline of 810km is currently under construction [100]. The discovery potential for these and future long baseline experiments is increased with the large value of $\sin^2(2\theta_{13})$ measured at Double Chooz (figure 7.20).

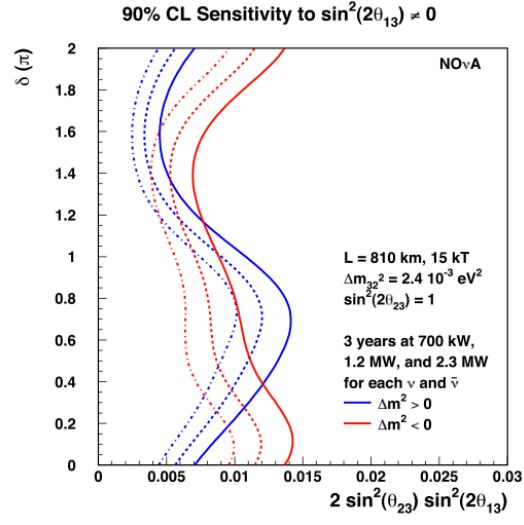


Figure 7.20: Nova's sensitivity to ν_e appearance. Blue curve is normal hierarchy and red curve is inverted [100]

Chapter 8

Conclusions

The Double Chooz far detector has now been running stable since April 13, 2011. The goals for the detector (signal to background ratio, scintillator light yield and stability, no electronic dead time, etc.) have been met or exceeded with the hard work of the 36 member institutions. The results from the first 101 days of data taking were first reported in November 2011 at the LowNu11 conference and published in the Physical Review Letters March 2012. With only the far detector running 4121 IBD candidate events resulted in a value for $\sin^2(2\theta_{13}) = 0.086 \pm 0.041 \text{ (stat)} \pm 0.030 \text{ (syst)}$. The Double Chooz far detector has continued to run as the near detector is constructed. A higher statistics result is in preparation for the Double Chooz far detector for release at the end of summer 2012. Once the near detector is running Double Chooz systematic will drastically be reduced resulting in a more precise determination of the neutrino oscillation mixing angle. The non-zero value for θ_{13} is an important step in the study of neutrino properties, which will impact future neutrino studies.

Over the past four and a half years I have contributed in the Double Chooz collaboration as part of the PMT group, detector commissioning, and data analysis cluster. I built and deployed the portable testing system used during several phases of installation at Chooz beginning with the testing of the Inner Veto and Inner Detector PMTs. I worked both onsite and remotely to support the DAQ commissioning. Most notable was the first characterization of PMT light noise in the detector. Several pieces of the portable testing system have become permanent fixtures in the far detector lab and will be duplicated for the near detector. As part of the US analysis cluster I contributed in the determination of IBD candidate criteria, final candidate extractions, and background estimations.

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Vita

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