

# **A Search for Short-Wavelength Neutrino Oscillation From a Nuclear Reactor**

---

A Dissertation  
Submitted to  
the Temple University Graduate Board

---

In Partial Fulfillment  
of the Requirements for the Degree  
**DOCTOR OF PHILOSOPHY**

---

by  
Danielle Berish Landschoot  
December 2019

Examining Committee Members:

Jim Napolitano, Department of Physics, Advisory Chair  
Maria Iavarone, Department of Physics  
C. Jeff Martoff, Department of Physics  
Don Jones, Department of Physics  
Michelle Dolinski, External Reader, Department of Physics, Drexel University

# ABSTRACT

The Precision Reactor Oscillation and SPECTrum Experiment (PROSPECT) is designed to probe short baseline oscillations of antineutrinos in search of eV-scale sterile neutrinos and precisely measure the  $^{235}\text{U}$  reactor antineutrino spectrum from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. The PROSPECT antineutrino detector (AD) provides excellent background rejection and position resolution due to its segmented design and use of  $^6\text{Li}$ -loaded liquid scintillator. Due to characteristics of its decay chain,  $^{227}\text{Ac}$  was added as a calibration source that was dissolved isotropically throughout the liquid scintillator. Using the correlated production of alphas from  $^{219}\text{Rn} \rightarrow ^{215}\text{Po} \rightarrow ^{211}\text{Pb}$  in the  $^{227}\text{Ac}$  decay chain we can measure the rate of  $^{227}\text{Ac}$  in each segment of the detector. This allows us to precisely determine the relative segment to segment volume variation to 1%. These measurements can then be applied as corrections to measurements of neutrino oscillation through the PROSPECT AD.

# **ACKNOWLEDGEMENTS**

These are the acknowledgements, where you express your appreciation to those who were influential and important to your success.

# TABLE OF CONTENTS

<b>ABSTRACT</b>	i
<b>ACKNOWLEDGEMENTS</b>	ii
<b>LIST OF FIGURES</b>	viii
<b>LIST OF TABLES</b>	ix
CHAPTER	
<b>1 INTRODUCTION</b>	1
<b>2 NEUTRINOS</b>	2
2.1 Discovery of the Neutrino . . . . .	2
2.2 Neutrinos in the Standard Model and Beyond . . . . .	4
2.3 Discovery of Neutrino Oscillation . . . . .	7
<b>3 REACTOR NEUTRINOS</b>	11
3.1 Production of Reactor Neutrinos . . . . .	11
3.2 Measuring the Reactor Antineutrino Flux and Spectrum . . . . .	12
3.3 Detection of Reactor Neutrinos . . . . .	14
3.4 The Reactor Antineutrino Anomaly . . . . .	15
<b>4 PROSPECT</b>	20
4.1 Experimental Site . . . . .	20
4.1.1 HFIR . . . . .	20
4.1.2 Backgrounds at HFIR . . . . .	21

4.2	Design . . . . .	22
4.2.1	Active Detector . . . . .	23
4.2.1.1	PMT Housings . . . . .	23
4.2.1.2	Optical Grid . . . . .	23
4.2.1.3	Segment Supports . . . . .	24
4.2.1.4	Radioactive Calibration System . . . . .	26
4.2.1.5	Liquid Scintillator . . . . .	28
4.2.2	Containment Vessels and Shielding . . . . .	29
4.3	Data Acquisition System . . . . .	30
<b>5</b>	<b>PROSPECT ANALYSIS FRAMEWORK AND CALIBRATION</b>	<b>31</b>
5.1	Pulse Shape Discrimination . . . . .	31
5.2	Data Processing and Calibration . . . . .	32
5.2.1	Timing to Position Curves . . . . .	33
5.2.2	Energy Calibration . . . . .	35
5.3	Monte Carlo Simulation . . . . .	36
5.3.1	Nonlinearity . . . . .	36
5.3.2	Energy Response . . . . .	37
5.3.3	Energy Resolution . . . . .	37
<b>6</b>	<b><math>^{227}\text{AC}</math> AS A CALIBRATION SOURCE</b>	<b>41</b>
6.1	Motivation . . . . .	41
6.2	Material Compatibility . . . . .	43
6.3	Event Selection in the PROSPECT AD . . . . .	43
6.4	Detector Stability Results . . . . .	43
6.5	Volume Variation Results . . . . .	43
<b>7</b>	<b>NEUTRINO OSCILLATION IN THE PROSPECT AD</b>	<b>44</b>
<b>8</b>	<b>CONCLUSIONS</b>	<b>45</b>
<b>BIBLIOGRAPHY</b>		<b>46</b>
<b>APPENDICES</b>		

A SOME ADDITIONAL STUFF	52
B MORE ADDITIONAL STUFF	53

# LIST OF FIGURES

2.1	Spectrum of solar neutrino fluxes . . . . .	8
3.1	Fission of $^{235}\text{U}$ . . . . .	12
3.2	The $\bar{\nu}_e$ spectrum. . . . .	13
3.3	The IBD spectrum. . . . .	16
3.4	Daya Bay $\bar{\nu}_e$ flux. . . . .	17
3.5	World average of reactor $\bar{\nu}_e$ flux. . . . .	17
3.7	Spectrums. . . . .	19
4.1	The HFIR core and flux distribution . . . . .	21
4.2	Layout of PROSPECT at HFIR . . . . .	22
4.3	Schematic of the PROSPECT detector . . . . .	23
4.4	Cross-section of inner detector . . . . .	24
4.5	PMT housing module . . . . .	24

4.6	Pinwheels . . . . .	25
4.7	Schematic of a segment . . . . .	25
4.8	Construction of a row . . . . .	25
4.9	Completed inner detector . . . . .	26
4.10	Source tube positions . . . . .	27
4.11	Source capsule on timing belt . . . . .	28
4.12	LiLS UV-Vis absorption spectra . . . . .	29
4.13	DAQ schematic . . . . .	30
5.1	Typical waveform . . . . .	32
5.2	PSD vs. psuedo-energy for neutron coincident events . . . . .	33
5.3	Muon $dt$ versus signal amplitude . . . . .	34
5.4	Muon $dt$ for a single segment . . . . .	34
5.5	$z(dt)$ curves for all cells . . . . .	34
5.6	Energy position dependence . . . . .	35
5.7	MC-data comparison of reconstructed energy . . . . .	39
5.8	MC-data reconstructed energy peak ratio for $\gamma$ sources . . . . .	40
6.1	Monte Carlo neutrino spectrum as a function of L/E . . . . .	41

6.2 $^{227}\text{Ac}$ decay chain . . . . .	42
---	----

# LIST OF TABLES

2.1	The Standard Model of Particle Physics . . . . .	4
2.2	Neutrino Oscillation Parameters . . . . .	10
4.1	Calibration sources . . . . .	27
6.1	. . . . .	43

# CHAPTER 1

## INTRODUCTION

# CHAPTER 2

## NEUTRINOS

### 2.1 Discovery of the Neutrino

The study of radioactive decay in the early 20th century exposed discrepancies that would lead to the postulation and eventual discovery of the neutrino. An experiment performed by Lise Meitner and Otto Hahn in 1911 offered some of the first evidence that the energy spectrum of electrons emitted by beta decay is continuous [1]. This was in stark contrast to the expected discrete spectra that had been observed in gamma and alpha emission, and suggested that three laws of conservation (energy, linear momentum, and angular momentum) were broken during beta decay. Their findings were later confirmed by experiments performed by Chadwick in 1914 [2] and Ellis and Wooster in 1927 [3].

At the time, beta decay was thought to be a two-particle decay, a process that yields a product nucleus and an electron. In 1930, Wolfgang Pauli postulated a particle he called the ‘neutron’, which would be ejected with the electron, thereby conserving energy and momentum. Describing his idea as a “desperate remedy”, this new particle would have to be neutral and non-interacting, therefore making it almost impossible to detect. In 1934, Enrico Fermi further developed the theory of beta decay, including Pauli’s particle but renaming it the neutrino, meaning “little neutral one” [4]. Due to the nature of the weakly interacting neutrino, experimental discovery would take another 20 years.

In 1956 Clyde Cowan and Fred Reines accomplished the amazing feat of discovering this elusive particle experimentally by taking advantage of the inverse beta decay (IBD) process [5]:

$$\bar{\nu} + p \rightarrow n + e^+ \quad (2.1)$$

Their idea was to place a detector near an intense source of neutrinos, fill it with an ample number of protons, and observe the resulting positrons. However, any source that generates a large enough flux of neutrinos will create large backgrounds for the experiment. As would become the challenge for every neutrino detector thereafter, Cowan and Reines had to devise a way to reduce the background such that they could obtain a measurable and believable number of neutrinos. Their original idea was to place a detector underground about 40 meters away from a fission bomb. This would create a large instantaneous flux of neutrinos providing a sufficient signal to background ratio.

After some thought, though, they realized that by detecting the neutron *and* the positron they could discriminate the IBD signal from the background with much higher success. This would allow the use of a nuclear reactor instead of a fission bomb as a neutrino source, giving them the opportunity to patiently watch for neutrinos rather than be restricted to one chance with a bomb. The final detector that would facilitate the discovery of the electron anti-neutrino,  $\bar{\nu}_e$ , contained 1400 liters of liquid scintillator viewed by 110 photomultiplier tubes and 200 liters of water with dissolved cadmium chloride, and was placed near the fission reactor at the Savannah River Plant in South Carolina.

The mechanisms behind the detector developed by Cowan and Reines worked as follows. Neutrinos from the reactor enter the detector and interact with protons in the water. The positron resulting from this reaction quickly collides with an electron, creating two gamma rays which Compton scatter and initiate a cascade of electrons that causes the liquid to scintillate. Simultaneously, the neutron from the initial reaction bounces around as it collides with protons until, eventually, it captures on a cadmium nucleus and releases about a 9 MeV gamma ray, also causing the liquid to scintillate. The time between the flash of light from the positron annihilation and that of the neutron capture is on the order of microseconds. It was by looking for this delayed-coincidence signature that Cowan and Reines were able to successfully detect the first neutrino, and thus pave the way for future neutrino experiments.

Only 6 years after the discovery by Cowan and Reines, Lederman, Schwartz, and Steinberger discovered the muon neutrino,  $\nu_\mu$  [6], but the discovery of the tau

	Fermions			Bosons	
	spin = 1/2			spin = 1	spin = 0
Generation	I	II	III	Gauge Bosons	Scalar Bosons
Quarks	u	c	t	g	H
	d	s	b	$\gamma$	
Leptons	e	$\mu$	$\tau$	Z	W
	$\nu_e$	$\nu_\mu$	$\nu_\tau$	W	

**Table 2.1:** The Standard Model of particle physics, composed of fermions and their corresponding antiparticles, the force carries (gauge bosons), and the Higgs boson.

neutrino,  $\nu_\tau$ , by the DONUT (Direct Observation of the Nu Tau) experiment would not occur until 44 years later [7, 8].

## 2.2 Neutrinos in the Standard Model and Beyond

The Standard Model (SM) of particle physics is the result of several decades of work by many scientists. It is a field theory that describes three of the four fundamental forces (electromagnetic, strong and weak), and classifies all known elementary particles as outlined in Table 2.1.

Classified in three generations of leptons, neutrinos exist in corresponding flavors, electron neutrinos ( $\nu_e$ ), muon neutrinos ( $\nu_\mu$ ), and tau neutrinos ( $\nu_\tau$ ), to the electron (e), muon ( $\mu$ ), and tau ( $\tau$ ) leptons, respectively. For each of these flavors a corresponding antiparticle also exists,  $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$ .

If neutrinos have exactly zero mass and travel at the speed of light, then by definition their helicity, or handedness, is a conserved property. Since experiments only measured left-handed neutrinos [9], it was assumed that all neutrinos in the SM were massless. As will be discussed in greater depth in Section 2.3, it was later experimentally discovered that neutrinos oscillate, or change flavors, indicating that at least two of the three neutrinos must have mass.

Their ability to oscillate arises from the fact that neutrinos exist as flavor eigenstates of the weak interaction,  $\nu_\alpha$ :  $\alpha = e, \mu, \tau$ , that are not identical to their mass states,  $\nu_i$ :  $i = 1, 2, 3$ , which are eigenstates of the Hamilton describing the free neutrino. This means that a neutrino produced at a source has a known flavor, but its mass is described as a superposition of all possible mass eigenstates, creating three possible scenarios: (i) The mass states are the same as the flavor states, therefore,

a neutrino produced as a  $\nu_x$  will remain  $\nu_x$  forever. (ii) The mass states and flavor states are different, but the mass states are all the same or all zero, therefore, a neutrino produced as  $\nu_x$  will still remain  $\nu_x$  because the combination of mass states does not change over time. (iii) The mass states and flavor states are different and at least two of the mass states are not the same, therefore, the phase between mass states will change as the neutrino propagates through time and space causing a change of flavor state. Experimental discoveries of neutrino oscillation require that the third scenario is correct.

Given this we can define the probability that a neutrino oscillates by first describing the flavor eigenstates as:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \quad (2.2)$$

where  $U_{\alpha i}$  is the unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix [10]. The PMNS matrix relates flavor to mass eigenstates and can be written in factorized form as:

$$U = \begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & s_{13}e^{-i\delta} \\ -s_{13}e^{i\delta} & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{pmatrix} \begin{pmatrix} 1 & e^{i\alpha} \\ & e^{i\beta} \end{pmatrix} \quad (2.3)$$

where  $s_{ij} = \sin \theta_{ij}$  and  $c_{ij} = \cos \theta_{ij}$ ,  $\theta_{ij} = [0, \pi/2]$ ,  $\delta = [0, 2\pi]$  is the Dirac charge parity (CP) violation phase, and  $\alpha$  and  $\beta$  are two Majorana CP violation phases.

As a neutrino,  $\nu_\alpha$ , propagates in time the mass eigenstates evolve differently (assuming that  $m_1 \neq m_2 \neq m_3$ ), resulting in a new flavor state,  $\nu_\beta$ . Massive neutrinos move through time and space as

$$|\nu_i(x, t)\rangle = e^{-\frac{i}{\hbar}(E_i t - \vec{p}_i \cdot \vec{x})} |\nu_i(0, 0)\rangle = e^{-i\phi} |\nu_i(0, 0)\rangle \quad (2.4)$$

The flavor state  $\alpha$  at some point in time and space can then be defined as:

$$|\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} |\nu_i(x, t)\rangle = \sum_i U_{\alpha i} e^{-i\phi_i} |\nu_i(0, 0)\rangle \quad (2.5)$$

Therefore, the oscillation probability that a neutrino produced as flavor  $\nu_\alpha$  will be

detected as flavor  $\nu_\beta$  after traveling for a period of time is given by

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\beta) &= |\langle \nu_\alpha(0,0) | \nu_\beta(x,t) \rangle|^2 \\
&= \left| \sum_i U_{\alpha i}^* e^{-i\phi_i} U_{\beta i} \right|^2 \\
&= \sum_i \sum_k U_{\alpha i}^* U_{\beta i} U_{\alpha k} U_{\beta k}^* e^{-i(\phi_i - \phi_k)}
\end{aligned} \tag{2.6}$$

This is true for any number of neutrino generations, but for the sake of simplicity, consider the case of two neutrino oscillation. In this scenario the mixing matrix can be written as

$$U = \begin{pmatrix} U_{\alpha 1} & U_{\alpha 2} \\ U_{\beta 1} & U_{\beta 2} \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} \\ -\sin \theta_{12} & \cos \theta_{12} \end{pmatrix} \tag{2.7}$$

Therefore, the probability of oscillation is given by

$$\begin{aligned}
P^{2\nu}(\nu_\alpha \rightarrow \nu_\beta) &= |U_{\alpha 1}|^2 |U_{\beta 1}|^2 + |U_{\alpha 2}|^2 |U_{\beta 2}|^2 + U_{\alpha 1}^* U_{\beta 1} U_{\alpha 2} U_{\beta 2}^* (e^{i(\phi_2 - \phi_1)} + e^{-i(\phi_2 - \phi_1)}) \\
&= \sin^2 2\theta_{12} \sin^2 \left( \frac{\phi_2 - \phi_1}{2} \right)
\end{aligned} \tag{2.8}$$

Now, recall that

$$\phi_i = \frac{1}{\hbar} (E_i t - \vec{p}_i \cdot \vec{x}) \tag{2.9}$$

The mass of the neutrino is very small compared to its energy ( $m_\nu \ll E_\nu$ ) so the momentum can be approximated as

$$p_i = \frac{1}{c} \sqrt{E_i^2 - m_i^2 c^4} = \frac{1}{c} \left( E_i - \frac{m_i^2 c^4}{2E_i} \right) \tag{2.10}$$

If it is reasonably assumed that neutrinos move at the speed of light,  $c$ , then the phase difference,  $\phi_2 - \phi_1$ , can be approximated as

$$\begin{aligned}
\phi_2 - \phi_1 &= \frac{1}{\hbar} \left( (E_2 - E_1) \frac{L}{c} - (p_2 - p_1)L \right) \\
&= \frac{1}{\hbar} \frac{L}{c} \left( \frac{m_2^2 c^4}{2E_2} - \frac{m_1^2 c^4}{2E_1} \right) \\
&= \frac{L}{\hbar c} \frac{\Delta m_{21}^2 c^4}{2E}
\end{aligned} \tag{2.11}$$

where  $t = \frac{L}{c}$ ,  $\Delta m_{21}^2 = m_2^2 - m_1^2$  and  $E_1 = E_2 = E$ .

It can now be shown that the oscillation probability of a neutrino  $\nu_\alpha$ , being detected as flavor  $\nu_\beta$  in the two neutrino mixing case is

$$P^{2\nu}(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta_{12}) \sin^2\left(\frac{c^4}{4\hbar c} \frac{\Delta m_{12}^2 L}{E}\right) \quad (2.12)$$

The corresponding survival probability, the chance that a neutrino  $\nu_\alpha$  is detected as  $\nu_\alpha$ , can be described by  $P^{2\nu}(\nu_\alpha \rightarrow \nu_\alpha) = 1 - P^{2\nu}(\nu_\alpha \rightarrow \nu_\beta)$ .

There are several aspects of note about this probability. It can be seen that the amplitude of the oscillation probability,  $\sin^2(2\theta_{12})$ , depends on the mixing angle  $\theta_{12}$ , while the mass splitting,  $\Delta m_{12}^2$ , the energy of the neutrino,  $E$ , and the distance traveled,  $L$ , determine the frequency of oscillation. The probability is non-zero only when  $\Delta m_{12}^2$  is non-zero, indicating that if an experiment observes neutrino oscillation, then at least one of the neutrinos must have mass. Finally, the dependence of oscillation on the factor  $\frac{L}{E}$  allows experiments to decide the placement of neutrino detectors based on what features of neutrinos they would like to study. Theoretical models alone do not prove neutrino oscillation, however. The first experimental evidence for oscillation and neutrino mass will be described in Section 2.3.

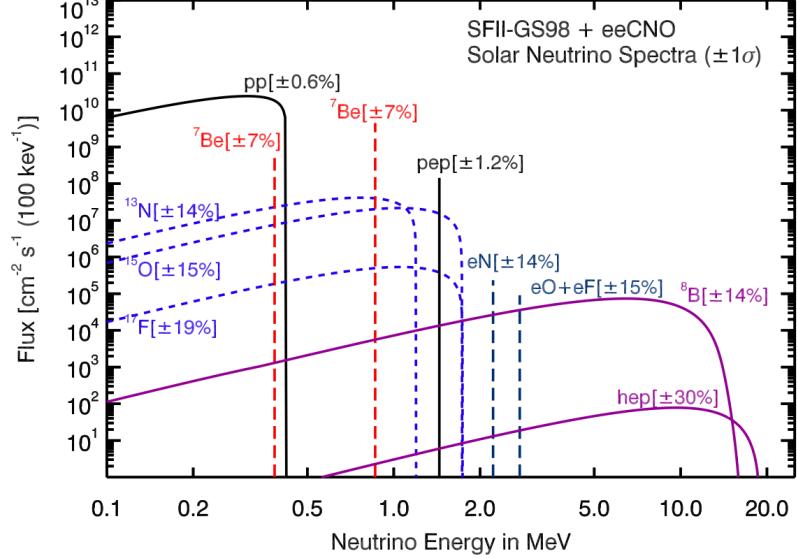
## 2.3 Discovery of Neutrino Oscillation

In the late 1960's, about a decade after Cowan and Reines discovered the first neutrino, astrophysicist John Bahcall and physical chemist Raymond Davis designed an experiment to collect and count solar neutrinos, neutrinos emitted by nuclear fusion taking place in the Sun. Davis placed a 380 cubic meter tank filled with perchloroethylene (dry-cleaning fluid) 1,478 meters underground in the Homestake Gold Mine in South Dakota. Perchloroethylene was chosen because it is rich in chlorine and the tank was placed deep underground to shield the experiment from cosmic rays.

Davis was looking for the reaction



in which a neutrino would enter the tank and transform chlorine into argon. Argon is a noble gas, making it easy to chemically separate from a large amount of chlorine-rich solvent. This allowed Davis to extract and count the argon atoms, essentially counting the number of neutrinos that had been captured. The chlorine reaction has



**Figure 2.1:** Spectrum of solar neutrino fluxes corresponding to the SFII-GS98 standard solar model. Electron capture CNO neutrinos (ecCNO) have been added in addition to standard fluxes. Electron capture fluxes are given in  $\text{cm}^{-2}\text{s}^{-1}$ . Figure from Ref. [11].

a threshold of 814 keV, which, according to standard solar models (see Figure 2.1), allowed the Homestake experiment to detect neutrinos created by  ${}^8\text{Be}$  in the sun (and  ${}^7\text{Be}$ ,  ${}^{13}\text{N}$ , and  ${}^{15}\text{O}$  at lower rates).

In the end, with the Homestake experiment Davis calculated a rate of solar neutrinos that was one third of the rate predicted by calculations made by Bahcall using the Standard Model [12]. This discrepancy became known as the solar neutrino problem, and in the following years Bruno Pontecorvo wrote several theoretical papers proposing neutrino oscillation as a solution [13, 14].

Several experiments designed to measure the flux of solar neutrinos followed the Homestake Experiment including SAGE [15], GALLEX [16], and GNO [17, 18]. All three experiments built detectors based on the reaction  ${}^{71}\text{Ga}(\nu, e^-){}^{71}\text{Ge}$  which has a threshold of 233 keV. This made them sensitive to neutrinos created by  $pp$  reactions in the Sun, neutrinos that the Homestake experiment was unable to measure. Even with the different energy threshold, though, all three experiments showed a deficit in neutrino flux compared to Standard Model calculations and the solar neutrino problem persisted.

Further experimental proof of neutrino oscillation came with results from the

Super-Kamiokande Experiment. Unlike previous experiments that were only sensitive to electron neutrinos, Super-K detected neutrinos through elastic scattering of electrons - a process sensitive to all neutrino flavors. Operating a high threshold of 4 MeV they observed pure  ${}^8\text{Be}$  solar neutrinos, a different selection than previous solar neutrino experiments. With their large mass, good energy resolution, and ability to determine neutrino directionality, Super-K was able to confirm the solar neutrino problem effect with high statistics and place limits on the parameters of oscillation [19].

The first direct evidence for solar neutrino flavor change came from the Sudbury Neutrino Observatory (SNO) in 2001 [20, 21]. The SNO detector was an imaging Cherenkov detector using heavy water. They were able to observe neutrino flavor change through three different processes: elastic scattering of electrons, the  $\nu_e - d$  charged current reaction (CC), and the  $\nu_x - d$  neutral current reaction (NC). The CC reaction has a threshold of -1.4 MeV, allowing SNO to accurately measure the shape of the  ${}^8\text{B}$  neutrino spectrum. The CC is also only sensitive to  $\nu_e$ , whereas the NC reaction is sensitive to all three active neutrino flavors, allowing SNO to compare measured fluxes from each reaction and ultimately confirm the theory of neutrino oscillation.

Nearly a century after the initial postulation of the neutrino the scientific community has in hand experimental evidence of three neutrino flavors, mathematical models that include these neutrinos in the Standard Model of Particle Physics, and theoretical and experimental proof that neutrinos oscillate and therefore have mass. These findings, along with developments in technology and techniques, set the stage for current, and future, neutrino experiments to transform their goals from observing anomalies to making precise measurements of the physics behind the anomalies. The current best-fit values of the 3-neutrino oscillation parameters as found experimentally are shown in Table 2.2.

Parameter	Best-fit	$3\sigma$
$\Delta m_{21}^2$ [10 <sup>-5</sup> eV <sup>2</sup> ]	7.37	6.93 - 7.96
$\Delta m_{31(23)}^2$ [10 <sup>-3</sup> eV <sup>2</sup> ]	2.56 (2.54)	2.45 - 2.69 (2.42 - 2.66)
$\sin^2 \theta_{12}$	0.297	0.250 - 0.354
$\sin^2 \theta_{23}$	0.425 (0.589)	0.381 - 0.615 (0.384 - 0.636)
$\sin^2 \theta_{13}$	0.0215 (0.0216)	0.0190 - 0.0240 (0.0190 - 0.0242)
$\delta/\pi$	1.38 (1.31)	2 $\sigma$ : 1.0 - 1.9 (2 $\sigma$ : 0.92 - 1.88)

**Table 2.2:** The current best-fit values and  $3\sigma$  allowed ranges of the 3-neutrino oscillation parameters as determined experimentally [10]. The values (values in brackets) correspond to  $m_1 < m_2 < m_3$  ( $m_3 < m_1 < m_2$ ).

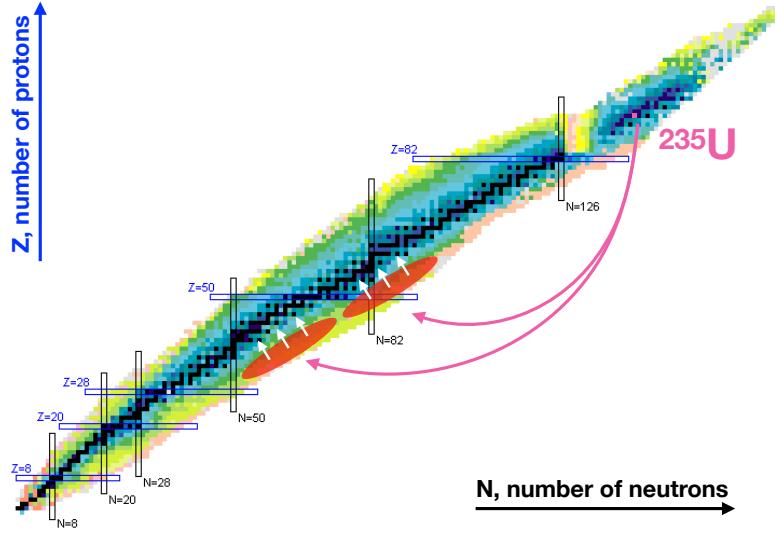
# CHAPTER 3

## REACTOR NEUTRINOS

Nuclear reactors are a pure source of electron antineutrinos,  $\bar{\nu}_e$ , as a result of the fission of isotopes used in the reactor fuel. The first neutrino was discovered using the nuclear reactor at the Savannah River Plant, and reactor sites continue to be popular homes for neutrino detectors. In order to perform precision reactor neutrino studies it is important to understand the reactor neutrino flux and spectrum.

### 3.1 Production of Reactor Neutrinos

Nuclear reactors are powered by the fission of uranium and plutonium isotopes in their cores. Specifically, in a power reactor, 99.9% of the power comes from the fission of  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ , and  $^{238}\text{U}$  isotopes. The reaction begins with a neutron colliding with a nucleus of one of the isotopes. This causes the nucleus to split into two fragments, usually of unequal mass, creating an unstable system. In order to reach stability neutrons have to transform into protons, a process accomplished through  $\beta$  decay, see Figure 3.1. Each beta decay produces an electron and corresponding electron antineutrino. In general a nuclear reactor will produce  $\sim 6 \times 10^{20} \bar{\nu}_e$  per GW of thermal energy power [22].



**Figure 3.1:** A schematic of the fission of  $^{235}\text{U}$  [23]. After collision with a neutron  $^{235}\text{U}$  will split into two unstable nuclei (pink arrows) which will then  $\beta$  decay (white arrows) until stable.

## 3.2 Measuring the Reactor Antineutrino Flux and Spectrum

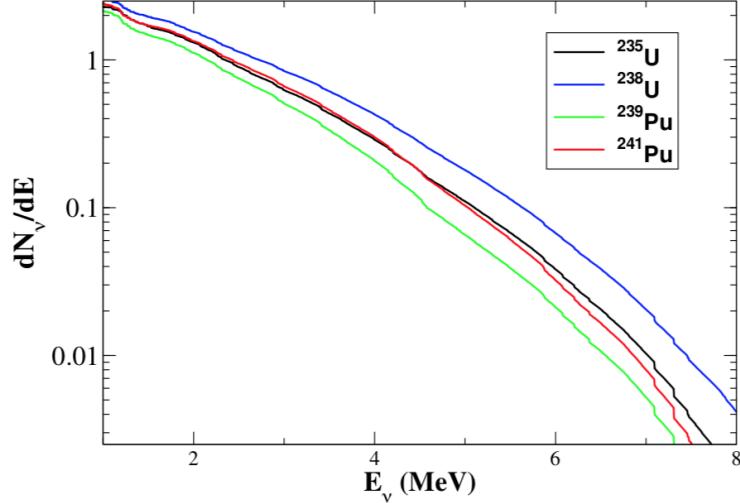
The total  $\bar{\nu}_e$  flux,  $S(E_\nu)$ , produced by a nuclear reactor can be expressed as the sum over the spectra of the dominant fissioning isotopes,

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i \frac{f_i}{F} \left( \frac{dN_i}{dE_\nu} \right), \quad (3.1)$$

where  $f_i/F$  is the fission fraction for each given isotope  $i$ ,  $W_{th}$  is the reactor thermal energy,  $e_i$  is the average energy released per fission by each isotope, and  $dN_i/dE_\nu$  is the cumulative  $\bar{\nu}_e$  spectrum of  $i$  normalized per fission.

There are two methods used to determine the  $\bar{\nu}_e$  spectrum, *ab initio* summation and electron spectrum conversion. In the *ab initio* approach the spectrum is determined by summing the contributions of all  $\beta$ -decay branches of all fission fragments,

$$\frac{dN_i}{dE_{\bar{\nu}}} = \sum_n Y_n(Z, A, t) \sum_{n,i} b_{n,i}(E_0^i) P_{\bar{\nu}}(E_{\bar{\nu}}, E_0^i, Z), \quad (3.2)$$



**Figure 3.2:** The  $\bar{\nu}_e$  spectrum predicted by the summation method using the JEFF-3.1.1 database fission fragment yields and the ENDF/B-VII.1 decay library [22].

where  $Y_n(Z, A, t)$  is the number of  $\beta$  decays of the fission fragment  $Z, A$  at time  $t$ ,  $b_{n,i}(E_0^i)$  are the branching ratios with endpoint energies  $E_0^i$ , and  $P_{\bar{\nu}}(E_{\bar{\nu}}, E_0^i, Z)$  is the normalized  $\bar{\nu}_e$  spectrum for the branch  $n, i$ . This method relies on nuclear databases, such as the Evaluated Nuclear Data File (ENDF) and Joint Evaluated Fission and Fusion (JEFF) databases, for information about the branching ratios and decay energies. The antineutrino spectrum for the four main reactor isotopes calculated using *ab initio* summation was done in Ref. [22] and the result can be seen in Figure 3.2.

Though seemingly straightforward, this approach comes with some caveats. The shear number of daughter isotopes ( $>1000$ ) and individual  $\beta$  decay branches ( $>6000$ ) make the summation non-trivial. This, along with the fact that not all branching ratios are known, and that the fission yields have been determined by several different database groups but don't always agree and have large uncertainties bring into question the validity of using only this method.

The other approach to determine the  $\bar{\nu}_e$  spectrum, the conversion method, relies on converting a measured electron spectrum into an antineutrino spectrum. This involves fitting an experimentally defined total beta spectrum with individual beta spectrum according to their amplitudes,  $a_i$ ,

$$\frac{dN_i}{dE_e} = \sum_i a_i P(E, E_0^i, Z) \quad (3.3)$$

The conversion to the antineutrino spectrum is then accomplished by replacing the energy  $E_e$  in each branch by  $E_0 - E_{\bar{\nu}}$ , because the electron and the  $\bar{\nu}_e$  share the total energy of each  $\beta$ -decay branch. The flux per fission is then given as the sum of  $\bar{\nu}_e$  spectrum converted from each virtual  $\beta$  branch,

$$\frac{dN_i}{dE_{\bar{\nu}}} = \sum_i a_i P(E_0^i - E, E_0^i) \quad (3.4)$$

The electron spectra for  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ , and  $^{241}\text{Pu}$  were measured at the Institut Laue-Langevin (ILL) reactor in Grenoble, France in the 1980s [24, 25, 26], while the spectrum of  $^{238}\text{U}$  was more recently (2014) measured at the neutron source FRMII in Garching, Germany [27]. The ILL measurements, along with a prediction of the  $^{238}\text{U} \bar{\nu}_e$  spectrum using the summation method by Vogel [28], became known as the “ILL-Vogel” flux model and was the main model used until 2011.

In 2011 Mueller *et al.* improved the prediction of the reactor antineutrino spectra by employing a method that combined information from the nuclear databases and the measured electron spectra from ILL [29]. This was followed by a further improvement by Huber who applied higher order corrections making use of the conversion method and minimizing the use of the databases as much as possible [30].

Though much work has been done to accurately model the reactor antineutrino spectra both methods are subject to uncertainties in the subdominant corrections to beta-decay. This includes radiative, weak magnetism, and finite size corrections along with uncertainties in the spectrum shape of forbidden transitions which are summarized in Ref.[22]. Besides the model uncertainties there are also experimental uncertainties that arise from knowing the thermal power of the reactor, its time-dependent fuel composition, and the fission energies of the dominant isotopes. All of these uncertainties result in a 10-20% relative uncertainty on the reactor antineutrino spectra using the *ab initio* method and  $\sim 5\%$  uncertainty on the conversion approach [31].

### 3.3 Detection of Reactor Neutrinos

Though there are several methods that can be used to detect reactor neutrinos, including charge-current ( $\bar{\nu}_e + d \rightarrow n + n + e^+$ ), neutral-current ( $\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$ ), and antineutrino-electron elastic scattering ( $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ ), the one employed by

most experiments is IBD ( $\bar{\nu}_e + p \rightarrow e^+ + n$ ). The IBD reaction energy threshold is 1.8 MeV and the cross section is relatively high,  $\sim 63 \times 10^{-44} \text{cm}^2/\text{fission}$  integrated over the entire reactor neutrino energy spectrum [31], and can be written as

$$\sigma^{(0)} \simeq 9.52 \times \left( \frac{E_e^{(0)} p_e^{(0)}}{\text{MeV}^2} \right) \times 10^{-44} \text{cm}^2 \quad (3.5)$$

where  $E_e$  and  $p_e$  are the energy and momentum of the final-state positron.

An IBD event is selected by a pair of coincident signals consisting of a positron ionization and annihilation as the prompt signal and a time delayed neutron capture on a proton or nucleus as the delay signal. The neutrino energy can be backtracked from the prompt signal as

$$E_{\bar{\nu}} = E_{prompt} + 0.78 \text{ MeV} + T_n \quad (3.6)$$

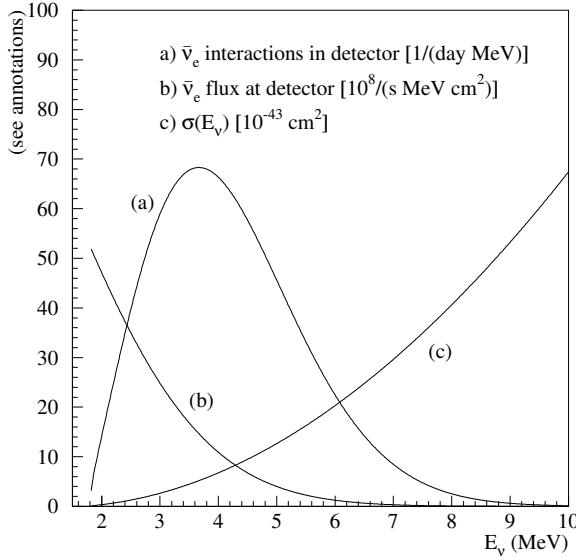
where  $T_n$  is the kinetic energy of the recoil neutron which is much smaller than the energy of the neutrino and can therefore be ignored in most cases. The IBD cross-section increases with energy, whereas the  $\bar{\nu}_e$  spectrum decreases with energy creating a detected energy spectrum that peaks around 3.8 MeV and dies off after  $\sim 8$  MeV, as seen in Figure 3.3.

In addition to great background rejection and good reconstruction of the neutrino energy, the IBD method of detecting neutrinos also allows the use of liquid scintillators and water as detection mediums.

### 3.4 The Reactor Antineutrino Anomaly

Several experiments have, and continue to use reactor antineutrinos as a probe of neutrino oscillation. A reactor neutrino disappearance  $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$  experiment located at a distance  $L \sim 1$  km can measure  $\sin^2 \Delta_{31}$ . At that baseline, the amplitude of the oscillation at the first maximum of  $\sin^2 \Delta_{31}$  is  $\sin^2 2\theta_{13}$  (recall Eq. 2.12), providing a direct measurement of  $\theta_{13}$ . Three experiments were designed to make a measurement of this mixing angle, Daya Bay in China, RENO in Korea, and Double Chooz in France.

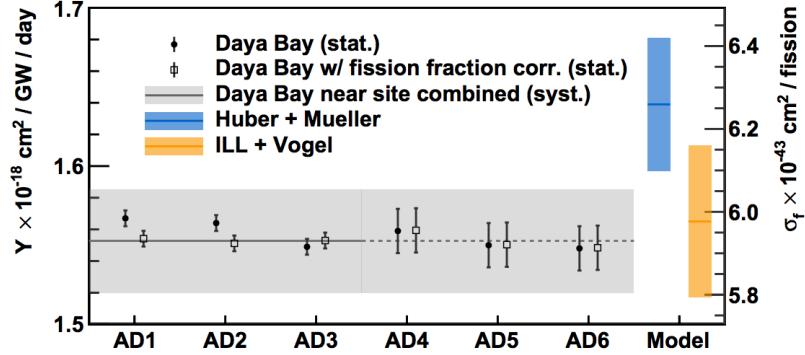
The Daya Bay Reactor Neutrino Experiment was located at the Daya Bay nuclear reactor power plant in southern China that consists of six 2.9 GW<sub>th</sub> reactors. They



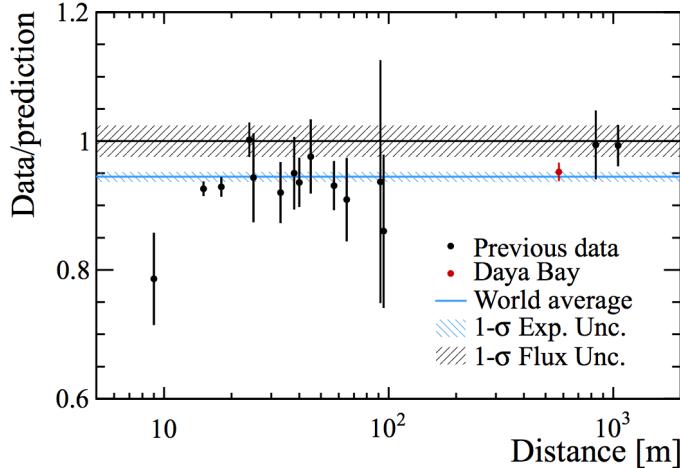
**Figure 3.3:** The IBD spectrum (curve (a)) measured by a 12-ton fiducial mass detector located 0.8 km from a 12-GW<sub>th</sub> power reactor along with the reactor flux (curve (b)) and IBD cross section (curve (c)) as a function of energy [10].

employed two groups of near (512 m, 561 m) and one group of far (1,579 m) antineutrino detectors (AD) in order to suppress the reactor flux uncertainties [32, 33]. The IBD yield measured for each AD is shown in Figure 3.4 and it can be seen that, after correcting for small variations of fission fractions among the different sites, all rates are consistent with each other. Though results between detectors agree, the disagreement between the experimental results and most recent model calculations (Huber+Mueller) is troubling.

In order to obtain a wider picture, the Daya Bay average IBD yield at the flux-weighted baseline (573 m) of the two near detector sites was compared to measurements from nineteen other short-baseline (<1000 m) experiments as shown in Figure 3.5. The global average, including the most recent Daya Bay calculation, results in a ratio of measured to expected yield of  $0.945 \pm 0.007$  (exp.)  $\pm 0.023$  (model) with respect to the Huber+Mueller model, a  $\sim 6\%$  deficit [34]. If the model uncertainty is to be trusted this ratio suggests reactor  $\bar{\nu}_e$  disappearance as close as  $L < 10$  m, a phenomenon not covered in the standard 3-flavor neutrino mixing model [22]. This predicament has been labeled the “reactor antineutrino anomaly” (RAA).

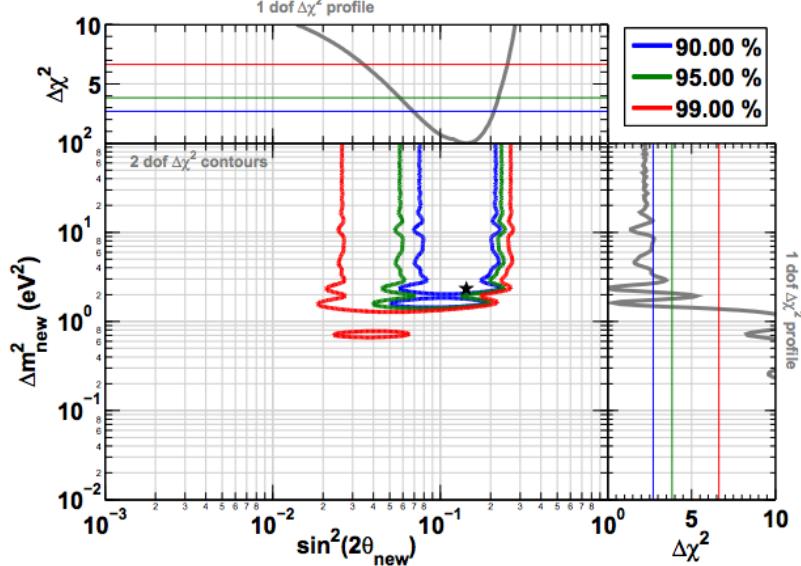


**Figure 3.4:** Rate of reactor antineutrino candidate events in Daya Bay’s six detectors [33]. The average of the three near detectors is shown as the gray line, extended though the far detectors as a dotted gray line. Also shown are the rates predicted using the Huber+Mueller (blue) and ILL+Vogel (orange) models.



**Figure 3.5:** The measured reactor  $\bar{\nu}_e$  rate, normalized to the Huber+Mueller model prediction, as a function of distance from the reactor [34]. The rate is corrected for 3-flavor neutrino oscillations at each baseline. The blue shaded region represents the global average and its  $1\sigma$  uncertainty. The  $2.7\sigma$  model uncertainty is shown as a band around unity.

One hypothesis for explaining the reactor anomaly is that reactor neutrinos are oscillating into a new type of neutrino, a sterile neutrino. A sterile neutrino is a right-handed neutrino that does not take part in weak interactions except those induced by mixing with active neutrinos [35]. Evidence for sterile neutrinos has also been observed in non-reactor neutrino experiments. Specifically, the Liquid Scintillation Neutrino Detector (LSND) measured an excess of  $\bar{\nu}_e$  ( $>3\sigma$ ) events [36] along with

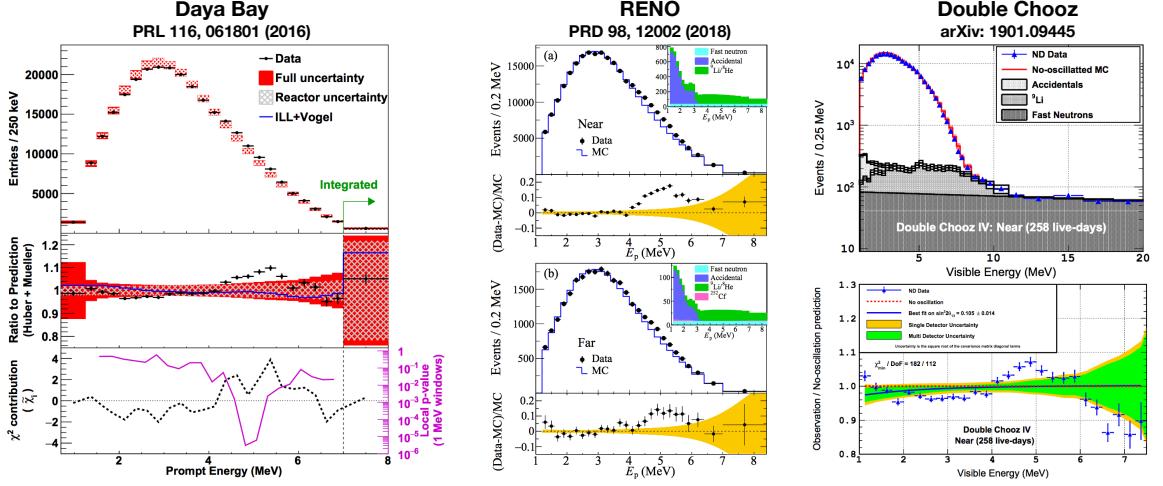


**Figure 3.6:** Allowed regions in the  $\sin^2(2\theta_{14}) - \Delta m_{14}^2$  plane resulting from a fit of the 3+1 neutrino model to results from reactor neutrino experiments, SAGE and GALLEX, MiniBooNE, and spectrum measurements from ILL. This global fit results in the constraints  $\Delta m_{14}^2 > 1.5 \text{ eV}^2$  and  $\sin^2(2\theta_{14}) = 0.14 \pm 0.08$  [39].

excesses measured by the Mini Booster Neutrino Experiment (MiniBooNE) of  $\nu_e$  ( $3.4\sigma$ ) and  $\bar{\nu}_e$  ( $2.8\sigma$ ) [37]. Two solar neutrino detectors, the SovietAmerican Gallium Experiment (SAGE) and Gallium Experiment (GALLEX), have observed a deficit in electron neutrinos produced by intense artificial  $^{51}\text{Cr}$  and  $^{37}\text{Ar}$  radioactive sources at a significance of  $3\sigma$  [38].

All of these anomalies hint at short-baseline oscillations of electron neutrinos. The simplest way to explain these discrepancies is to add onto the standard model using the 3+1 oscillation model in which there are three active neutrinos and one sterile. This would introduce three new mixing angles,  $\theta_{14}$  being the one of interest in reactor neutrino experiments. A global fit of this model to neutrino data, including results from reactor experiments, SAGE and GALLEX, MiniBooNE, and spectrum measurements from ILL, result in oscillation constraints  $\Delta m_{14}^2 > 1.5 \text{ eV}^2$  and  $\sin^2(2\theta_{14}) = 0.14 \pm 0.08$ , as shown in Figure 3.6 [39].

An alternative explanation is that the flux predictions are incorrect and have larger uncertainties than those currently applied. The idea that the calculated reactor antineutrino flux is not well understood is bolstered by results from Daya Bay [33], RENO [40], and Double Chooz [41] in which a “bump” was observed in the



**Figure 3.7:** A comparison between the predicted and measured prompt energy spectra of IBD events in Daya Bay [33], RENO [40], and Double Chooz [41]. All experiments observe an excess of events above uncertainty in the model spectrum in the 4-6 MeV region.

experimentally measured antineutrino energy spectrum relative to the model spectrum, shown in Figure 3.7. Whether either or both hypothesis are true, and solve the reactor antineutrino anomaly, is a topic of great interest in the neutrino community and several experiments have been designed to address this matter.

# CHAPTER 4

# PROSPECT

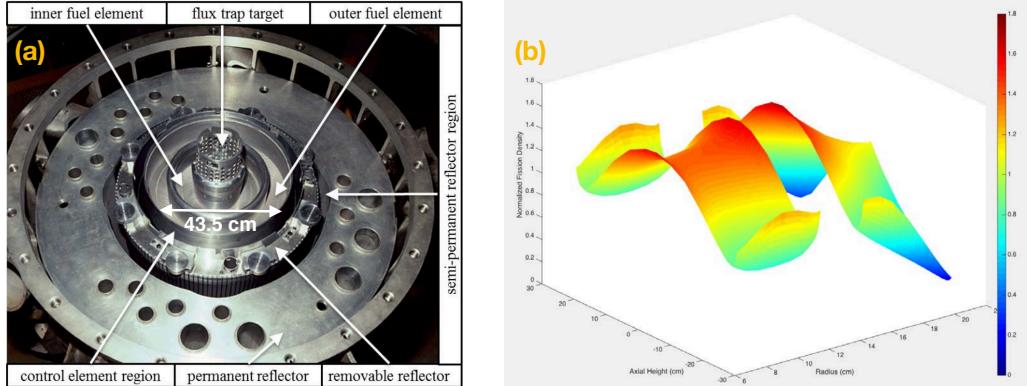
The scientific community’s understanding of neutrinos has come a long way from Pauli’s initial proposition of its existence in 1930. Though three active neutrino flavors and their behaviors are understood and well included in the Standard Model of particle physics, recent anomalies in reactor neutrino experiment results hint at the possibility of new physics. The discovery of an eV-scale sterile neutrino would have wide ranging impacts on the field of neutrino physics and future experiments.

The Precision Reactor Oscillation and Spectrum Experiment (PROSPECT) is designed to address the reactor antineutrino anomaly by performing a reactor-model independent search for short-baseline  $\bar{\nu}_e$  oscillations and making a high precise measurement of the  $^{235}\text{U}$   $\bar{\nu}_e$  energy spectrum at a highly-enriched uranium (HEU) research reactor [42]. Located at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) in Tennessee PROSPECT also demonstrates successful application of techniques for antineutrino detection at the surface with little overburden. PROSPECT collected data from May to December of 2018 and the first oscillation and spectrum results, with 33 and 40.3 live-days of reactor on time respectively, can be found in Ref.[43, 44].

## 4.1 Experimental Site

### 4.1.1 HFIR

HFIR is a compact research reactor that burns highly enriched uranium fuel ( $^{235}\text{U}$ ), meaning that  $> 99\%$  of fissions during a reactor cycle will be from  $^{235}\text{U}$ . The HFIR



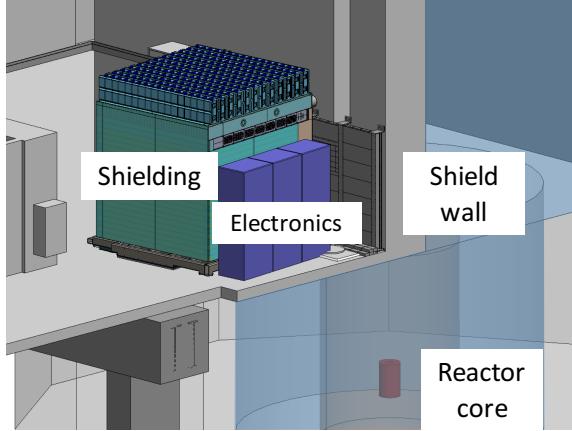
**Figure 4.1:** (a) The HFIR core, showing the inner and outer fuel elements and the flux trap region, as well as the control elements and Beryllium reflectors. (b) The relative fission density distribution at the start of a cycle. [45]

core consists of two concentric fuel elements with an outer diameter of 0.435 m and a height of 0.508 m, surrounded by control elements and Beryllium reflectors as shown in Figure 4.1. The reactor typically operates at 85 MW for seven 24-day cycles per year for a duty cycle of  $\sim 46\%$ .

#### 4.1.2 Backgrounds at HFIR

The PROSPECT detector is located at ground level  $\sim 7$  m from the HFIR core and separated from the reactor water pool by a 1 m thick concrete wall, show in Figure 4.2. The proximity to the reactor and lack of overburden introduces a significant level of background events from the reactor and cosmogenic sources. These events can be classified into two categories, (i) singles that are mainly due to gammas and (ii) coincident events from neutron recoil and captures. Extensive studies on the types and rate of background events at the detector site can be found in Refs.[46, 47, 48].

The largest source of gamma backgrounds was discovered to originate in the reactor pool wall, specifically an unused beam line that lies directly in front of the detector. In order to lower these backgrounds a lead shield wall (3.0 m wide, 2.1 m tall, and on average 0.10 m thick), along with shorter flanking walls on each side and a mini-wall placed at the opening of the beam line, was installed between the pool wall and the detector. Other background events were shown to come from neutron beam-lines and scattering experiments existing below the detector site, but most of these are suppressed by a concrete monolith that the detector sits on.

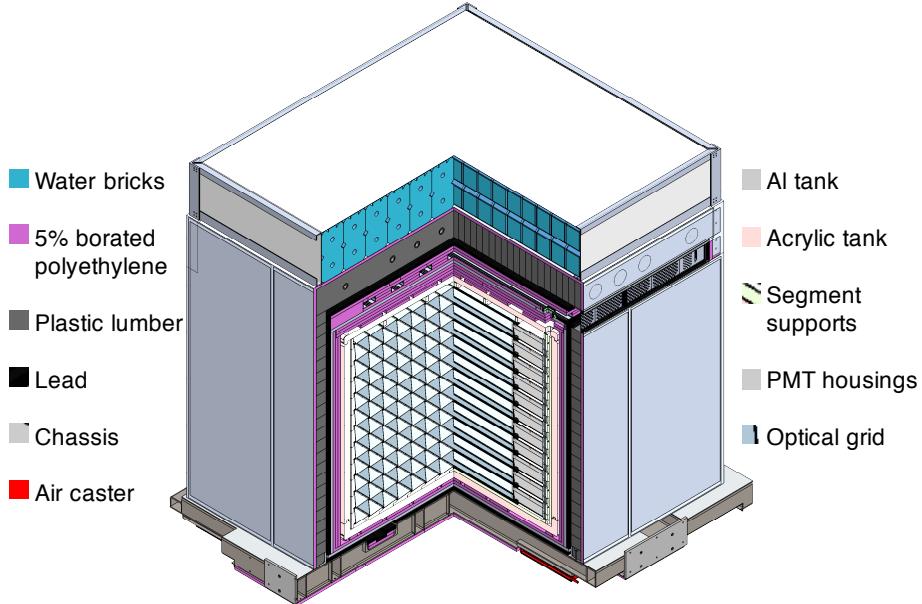


**Figure 4.2:** Layout of the PROSPECT experiment. The detector is installed in the HFIR Experiment Room next to the water pool and 5 m above the HFIR reactor core (red). The floor below contains multiple neutron beam-lines and scattering experiments.

The thermal neutron rate was measured to be  $\sim 2/\text{cm}^2/\text{s}$  during reactor operation [46], so layers of shielding containing  $^{10}\text{B}$ , which has a large thermal neutron cross-section and minimal gamma emission, were used in the passive shielding that surrounds the detector (see Section 4.2.2). The locally installed shield wall, along with the addition of passive shielding, resulted in a sufficient suppression of background such that a better than one-to-one signal to background ratio was achieved.

## 4.2 Design

The PROSPECT antineutrino detector (AD) consists of a segmented inner detector filled with  $^6\text{Li}$  doped liquid scintillator (LiLS), contained in an acrylic and aluminum tank, and surrounded by layers of passive shielding. The active detector is made up of a  $14 \times 11$  array of optically separated segments, viewed on each end by a photomultiplier tube (PMT) enclosed in an acrylic housing. The AD is placed with the segments parallel to the reactor pool wall,  $\sim 7$  m from the reactor core, and measures  $\sim 3$  m tall including all shielding. See Figure 4.3 for a schematic of the detector.



**Figure 4.3:** A cutaway view of the PROSPECT detector, including the inner detector, outer containment vessels, and passive shielding.

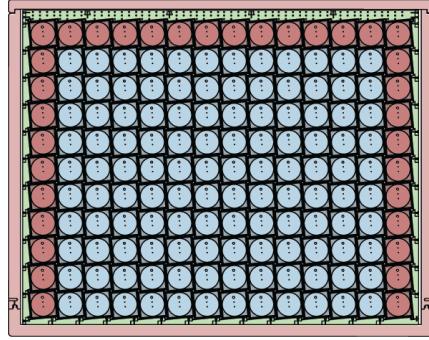
## 4.2.1 Active Detector

### 4.2.1.1 PMT Housings

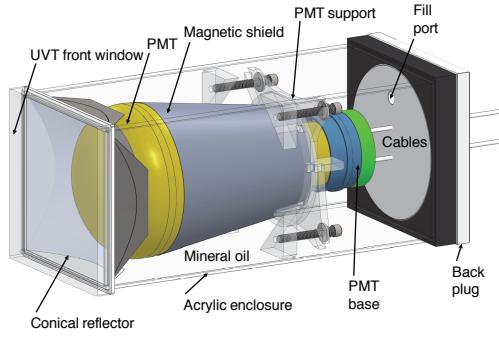
A total of 308 PMTs are installed in the AD; 240 Hamamatsu R6594 SEL PMTs used in the inner segments (fiducial volume) and 68 ADIT Electron Tubes 9372KB PMTs used in the outer segments as shown in Figure 4.4. Each PMT is mounted inside a rectangular acrylic housing facing a clear 144-mm-square front window constructed from ultraviolet transmitting (UVT) acrylic, allowing them to exist inside of the LiLS. Conical reflectors were installed at the face of the housing to improve light collection efficiency in the corners. The housing is filled with optical grade mineral oil and sealed with an O-ring and a 32-mm-thick back plug. For a detailed drawing of the PMT housing module see Figure 4.5. For more information on the PMT housing design and construction see Ref.[42].

### 4.2.1.2 Optical Grid

The active volume of the detector, measuring  $2.045\text{ m wide} \times 1.607\text{ m high} \times 1.176\text{ m long}$ , is separated into 154 optically separated long segments with a  $0.145\text{ m} \times 0.145\text{ m}$  square cross-sectional area. The optical grid that creates the individual segments



**Figure 4.4:** A cross-section of the inner AD showing 68 ET PMTs (red) in the outer columns and top row and 240 Hamamatsu PMTs (blue) in the remaining segments.



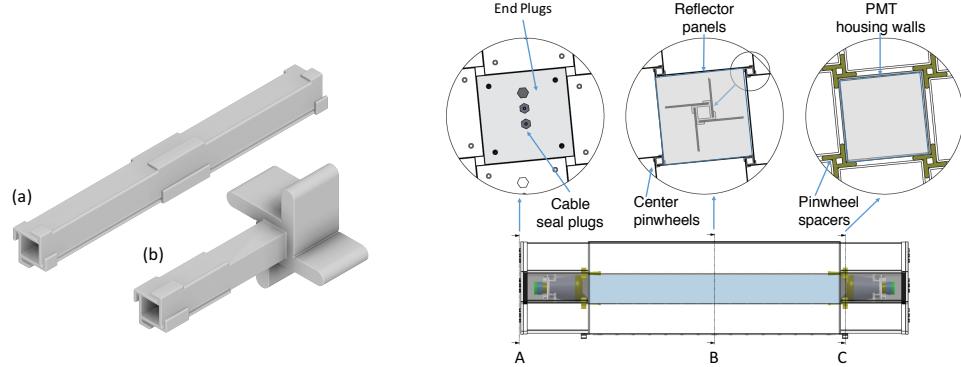
**Figure 4.5:** A PMT housing module.

consists of low-mass, highly specularly reflective optical separators held in position by white 3D-printed support rods. The optical separators (reflectors) are composed of a carbon fiber backbone covered on both sides with adhesive-backed 3M DF2000MA specularly reflecting film, an optically clear adhesive film, and a thin surface layer of fluorinated ethylene propylene (FEP) film. Two types of pinwheel shaped support rods were produced and strung on acrylic rods to grip the reflectors and hold them in place and separate the PMT housings from each other. The pinwheels were 3D printed using white-dyed 100-micron polylactic acid (PLA) filament and are pictured in Figure 4.6. For more details on the fabrication of the optical grid see Ref.[49].

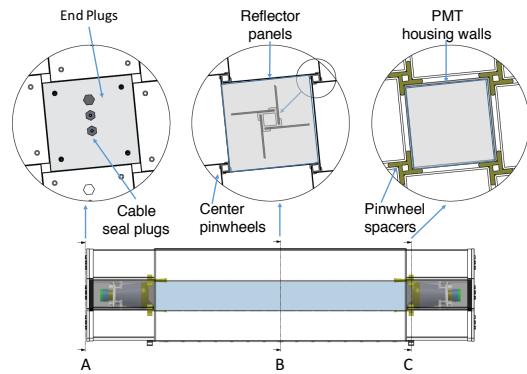
Each segment contains a PMT housing at each end and four reflectors held in place by pinwheel rods that extend from one PMT to the other, as shown in Figure 4.7. The front windows of the PMT housings protrude  $\sim 1$  cm into the optical grid, minimizing cross-talk between segments. Figure 4.8 shows the assembly of the top row of the detector, demonstrating the placement of the housings and optical grid.

#### 4.2.1.3 Segment Supports

While the optical grid creates the inner volume segmentation, acrylic segment supports hold the total volume in place and determine the size of the active volume. A slab of ship-lap style acrylic underneath the bottom row of segments position them at a  $5.5^\circ$  tilt with a 0.146 m pitch. Horizontal planks are screwed onto the backs



**Figure 4.6:** Representative pinwheel types. (a) Central pinwheel - Three tabs per side hold the optical separator in place. (b) End pinwheel - spacer arms separate the PMT housing bodies and support the pinwheel string.

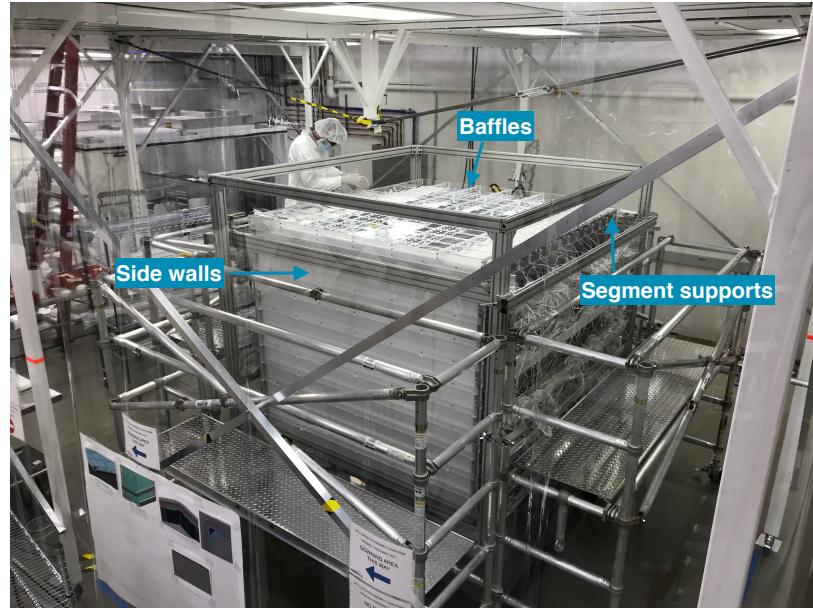


**Figure 4.7:** Three complete segments, including PMT housings at each end with reflectors kept in place between segments by pinwheel rods.



**Figure 4.8:** Assembly of the top row of the PROSPECT AD, demonstrating the placement of the PMT housings and optical grid.

of the PMT housings and attach together along the sides of the volume, while side walls constrain the outer pinwheel rows. Baffles at the top of the detector tie the four surrounding walls together and keep the top reflector layer in place. The construction of the inner detector, including all segment supports, allows the liquid scintillator to flow around all objects and therefore fill the whole space. For a photograph of the constructed inner detector see Figure 4.9.



**Figure 4.9:** A photograph of the constructed inner detector.

#### 4.2.1.4 Radioactive Calibration System

The radioactive calibration system is designed to measure and calibrate the energy and position response of the detector as well as to study topological effects. It does this by moving radioactive sources through a system of tubes routed throughout the active detector, the positions of which are pictured in Figure 4.10. PROSPECT deploys  $^{137}\text{Cs}$ ,  $^{22}\text{Na}$ ,  $^{60}\text{Co}$ ,  $^{252}\text{Cf}$ , and an AmBe source, the features of which are listed in Table 4.1.

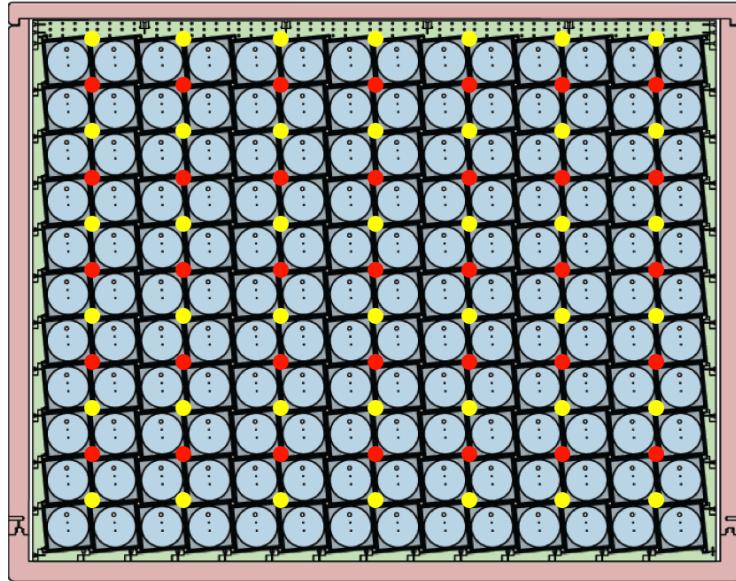
Each source is encapsulated in a small aluminum cylinder, about 12 mm long, and then connected to a timing belt as pictured in Figure 4.11. The timing belts are placed in source tubes that run along the length of the segments and are controlled

Source	Decay	$\gamma$ Energy [MeV]	Purpose	Rate
$^{137}\text{Cs}$	$\beta^-$	0.662	segment comparison	$0.1 \mu\text{C}$
$^{22}\text{Na}$	$\beta^+$	$2 \times 0.511, 1.275$	positron, edge effects	$0.1 \mu\text{C}$
$^{60}\text{Co}$	$\beta^-$	1.173, 1.332	energy scale	$0.1 \mu\text{C}$
$^{252}\text{Cf}$	n (fission)	2.223 (n-H capture)	neutron response	866 n/s
AmBe	n	4.4	neutron response	70 n/s

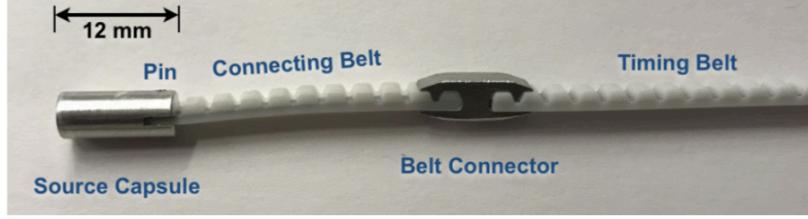
**Table 4.1:** Calibration sources and their properties.

by motors mounted outside of the detector volume. For more information on the construction of the calibration system see Ref.[50].

PROSPECT also makes use of intrinsic radioactive sources for calibration and monitoring of detector characteristics. Two of these are colloquially known as “BiPo” decays, and they arise from the  $^{212}\text{Bi} \rightarrow ^{212}\text{Po} + \beta \rightarrow ^{208}\text{Pb} + \alpha$  and  $^{214}\text{Bi} \rightarrow ^{214}\text{Po} + \beta \rightarrow ^{210}\text{Pb} + \alpha$  decay chains which stem from naturally occurring  $^{232}\text{Th}$  ( $t_{1/2} = 14$  Gyr) and  $^{238}\text{U}$  ( $t_{1/2} = 4.5$  Gyr), respectively. Along with these, a solution of  $^{227}\text{Ac}$  was added to the liquid scintillator to provide a source of “RnPo” decays from the chain  $^{219}\text{Rn} \rightarrow ^{215}\text{Po} + \alpha \rightarrow ^{211}\text{Pb} + \alpha$ . Further details on the motivation and results from adding actinium will be discussed in Chapter 6.



**Figure 4.10:** Location of the source tubes (red) routed through the active detector volume.



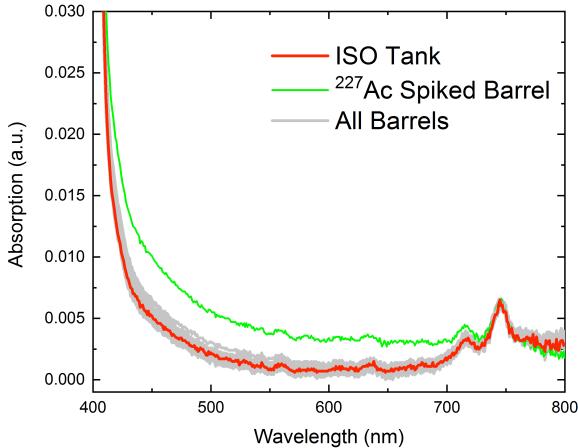
**Figure 4.11:** An example of a source capsule attached to the timing belt.

#### 4.2.1.5 Liquid Scintillator

The liquid scintillator (LS) used in PROSPECT needed to accomplish two goals: (i) provide very good pulse shape discrimination (PSD) for sufficient background rejection of fast neutrons and ambient gammas and (ii) have high light yield in order to obtain good energy resolution. The LS also needed to remain stable over time and non-flammable according to facility requirements. In order to accomplish these tasks PROSPECT developed a novel lithium-doped liquid scintillator (LiLS).  ${}^6\text{Li}$  was chosen as the doping agent due to it's high neutron capture cross section, which produces an  $\alpha$  and a  ${}^3\text{H}$  with about 540 keV of visible energy in the scintillator. These particles are also spatially localized, which is necessary for the compact detector size of PROSPECT.

The LiLS was created by adding a surfactant to the base LS which allowed the addition of a  ${}^6\text{LiCl}$  solution to obtain a final doping of  $0.082\%\pm0.001\%$  by mass. The combination of the surfactant and chloride solution forms a thermodynamically stable micro emulsion, ensuring material uniformity and allowing the addition of an actinide chloride solution ( ${}^{227}\text{Ac}$ ). A total of 5,040 liters were produced and stored in 28 separate drums. One drum was doped with a  ${}^{227}\text{Ac}$  chloride solution. For more information on the fabrication of the LiLS see Ref.[51].

Prior to filling the detector, all drums of LiLS were pumped into an ISO tank storage container. Nitrogen was then bubbled through the liquid for ten days to sufficiently mix together the solution. Samples were taken from each barrel and from the mixed solution in the ISO tank with a Shimadzu UV-Vis spectrometer, the results of which can be seen in Figure 4.12. 4841 kg of LiLS was pumped into the ISO tank and a total of 4340 kg was then added to the detector. For more information on the process of filling the detector with the LiLS see Ref.[42].



**Figure 4.12:** UV-Vis absorption spectra of the 28 drums if LiLS (gray+green) added to the ISO tank. The only outlier is the  $^{227}\text{Ac}$  spiked barrel (green). The mixed sample (red) falls within the average of all individual barrels.

#### 4.2.2 Containment Vessels and Shielding

The inner primary containment vessel is made of acrylic and holds all active detector components described in Section 4.2.1. The acrylic tank was built as three separate parts, the base, vertical walls, and lid. The inner detector was assembled on the acrylic base. After its constructions the vertical walls were lowered onto the base and secured with a Viton seal at the base.

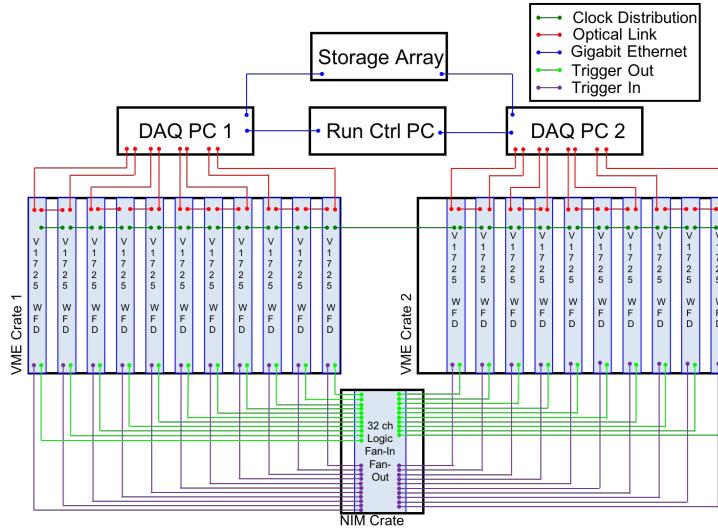
The secondary containment vessel is made of aluminum and the top is sealed in order to control the gas environment around the detector. The space between the aluminum and acrylic tanks is filled with sheets of borated polyethylene and demineralized water for absorption of thermal neutrons.

A lead layer of  $0.025\text{ m} \times 0.10\text{ m} \times 0.30\text{ m}$  interlocking brick was stacked around the perimeter of the aluminum tank. Rows of  $0.10\text{ m} \times 0.10\text{ m}$  recycled polyethylene lumber were stacked on each other log cabin style and then placed around the lead layer. Polyethylene lumber was also used to create roof beams on top of the log cabin walls. The entire surface was then covered with a  $0.025\text{ m}$  thick layer of borated polyethylene and thin aluminum sheets. To complete the passive shielding an array of water bricks were added to the top of the assembly. For a schematic of the entire construction see Figure 4.3.

## 4.3 Data Acquisition System

In order to perform pulse discrimination analysis of LiLS signals PROSPECT uses commercial Waveform Digitizer Modules (WFDs). A total of twenty-one CAEN V1725 WFD modules, operated in two Weiner 6023VME crates, are used to readout the 308 PMTs. Readout and control of the WFD modules is performed by two individual PCs, which are run by a control PC. A single Phillips Scientific 757D NIM Fan-In/Fan-Out module operated in a NIM bin is used for trigger signal distribution. A diagram of this system can be seen in Figure 4.13.

Acquisition of waveforms 148 samples long by all WFD channels is triggered if both PMTs in any segment exceed a signal level of 50 ADC counts above baseline ( $\sim 100$  keV) within a 64 ns coincidence window. Acquired samples from each WFD are only recorded to disk if they exceed a threshold limit of 20 ADC counts above baseline ( $\sim 40$  keV). These are labeled the segment and Zero Length Encoding (ZLE) thresholds and allow the acceptance of low energy events while maintaining a manageable data collection. For more information of the data acquisition system and data rates see Ref. [42].



**Figure 4.13:** Diagram of the data acquisition system.

# CHAPTER 5

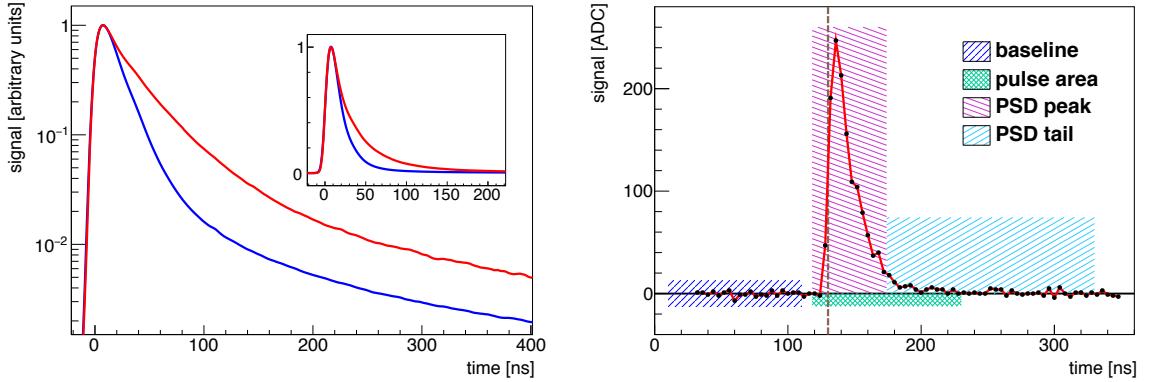
## PROSPECT ANALYSIS FRAMEWORK AND CALIBRATION

Events in the PROSPECT detector begin as bursts of scintillation in the liquid scintillator. In order to transform these events of light into physics data several steps have to be taken, including position reconstruction and energy calibration. This chapter will outline how these processes are performed, but before that is done a key component of the PROSPECT analysis, pulse shape discrimination, must be presented.

### 5.1 Pulse Shape Discrimination

Physics events in the PROSPECT detector, such as neutron captures on  ${}^6\text{Li}$ , produce scintillation light through ionization that is transported by way of the reflecting panels to individual PMTs. As described in Section 4.3, these signals are processed by CAEN waveform digitizers and are only accepted if they pass the segment and ZLE thresholds. Due to the nature of the liquid scintillator the shape of the digitized waveforms is defined by the ionization density of a given event. Lower ionization density events, such as electrons, have a faster scintillator decay time causing less light in the “tail” of the waveform compared to higher density events like proton recoils, as seen in Figure 5.1.

This allows the definition of a pulse shape discrimination (PSD) factor as the ratio



**Figure 5.1:** (Left) Averaged waveforms from electrons (lower, blue) and proton recoils (upper, red) [52]. The inset panel shows the same waveforms on a linear y axis. (Right) Example analysis of a typical pulse [53]. The half-height leading edge timing (dashed vertical) determines windows for baseline subtraction, pulse area, and PSD.

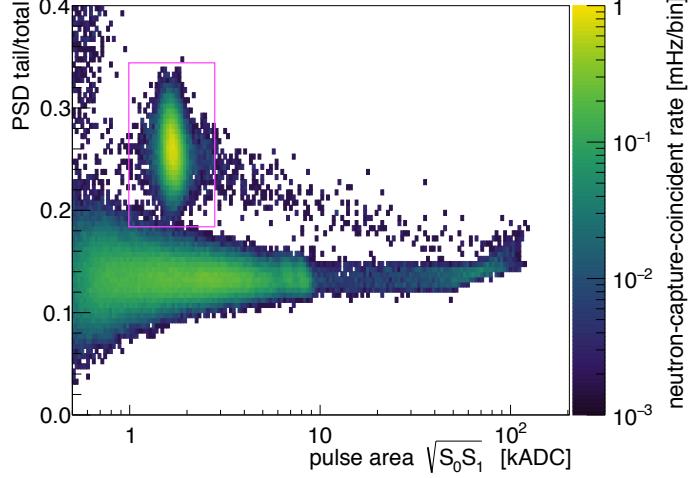
of the signal in the tail versus the total waveform,

$$PSD = \frac{\int_{tail:start}^{tail:end} Qdt}{\int_{-\infty}^{\infty} Qdt} \quad (5.1)$$

The tail area of a given waveform is defined as the window 44 - 100 ns after the time of the half-height leading edge. The total area is defined as the window -12 - 100 ns relative to the same leading edge time. An example of these windows on a typical pulse can be seen in Figure 5.1. Use of the PSD parameter, along with energy, provides clear separation between neutron captures on  ${}^6\text{Li}$  and other event classes such as electron recoils. An example of this for a single segment can be seen in Figure 5.2, where a pseudo-energy is calculated using the integrated pulse area of each PMT,  $S_0$  and  $S_1$ .

## 5.2 Data Processing and Calibration

For simplicity consider one event contained in one segment. Both PMTs in the segment will collect photons from this event that are saved as individual waveforms. These are analyzed and information such as pulse area and height in analog-to-digital converter (ADC) units, PSD, and arrival time are saved. The next step involves combining information from both PMTs, calibrating the energy, and reconstructing the position.



**Figure 5.2:** PSD vs. pseudo-energy for neutron capture coincident events in a single segment [54]. The neutron captures, outlined by the magenta rectangle, are clearly separated in PSD from electron-like events in the lower band.

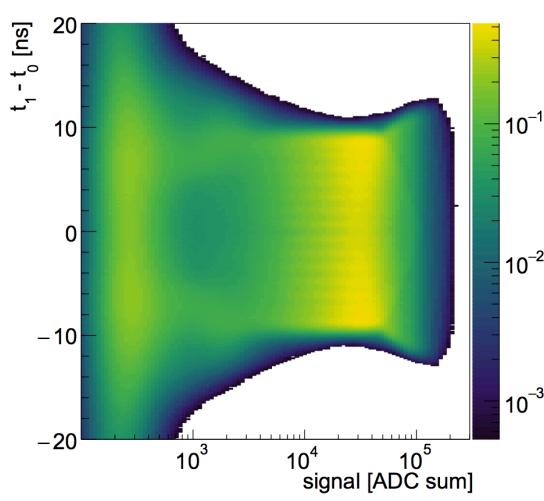
### 5.2.1 Timing to Position Curves

Through-going muons provide a large and consistent data set which can be used to reconstruct positions based on timing. As muons travel through the pinwheel rod tabs the light transport is distorted in timing and magnitude. This creates a striping effect in the timing between the two PMTs,  $dt$ , versus the signal amplitude ( $S_0 + S_1$ ) distribution as shown in Figure 5.3.

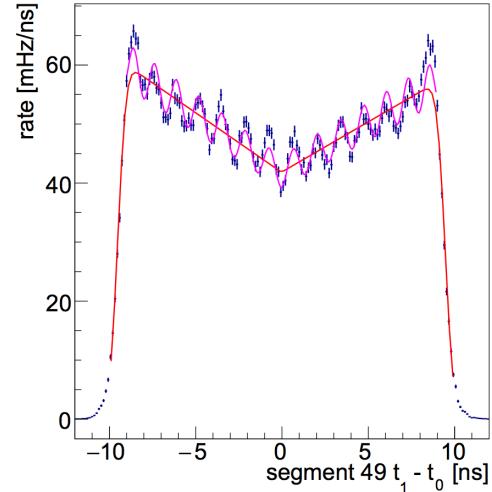
The striping becomes even clearer when plotting  $dt$  for events with signal amplitudes in the range  $1e4 - 2e4$  ADC for a single segment as shown in Figure 5.4. For each segment this distribution is first fit with an ‘‘M’’-shaped curve,  $M(dt)$ . Then, the residual structure is fit to a sinusoidal curve with a slowly varying phase shift term,

$$n(dt) = M(dt) \left[ 1 + k \cos \left( \frac{2\pi}{\delta} (a dt + b dt^3) \right) \right] \quad (5.2)$$

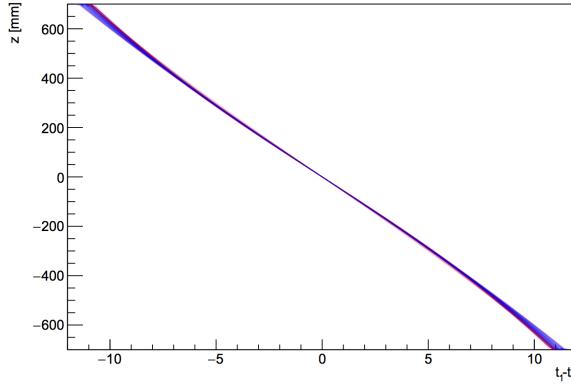
where  $\delta = 78.5$  mm is the average spacing between pinwheel tabs, and  $k, a, b$  are fit parameters. The inner phase term provides the position calibration  $z(dt) = a dt + b dt^3$ , whose resulting curves are shown in Figure 5.5.



**Figure 5.3:**  $dt$  versus signal amplitude for through-going cosmogenic muons [55]. Striping is visible at time intervals corresponding to pinwheel placement.



**Figure 5.4:**  $dt$  of through-going muons in a single segment for events with signal amplitudes in the range  $1e4 - 2e4$  ADC [55]. Data (blue points) are fit with an “M”-shaped curve (red) and a sinusoidal curve (magenta).



**Figure 5.5:**  $z(dt)$  curves for all cells, extracted from fitting muon  $dt$  distributions [55]. Blue: Hamamatsu segments, red: ET segments.

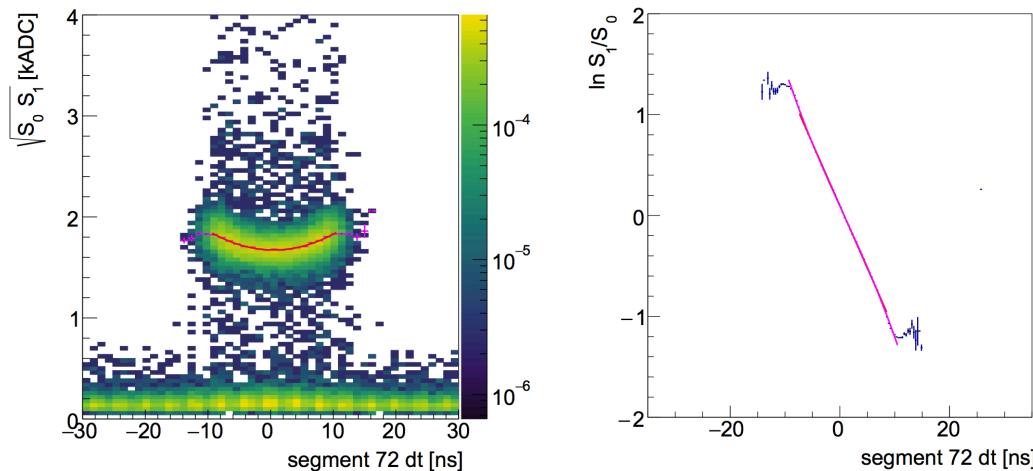
### 5.2.2 Energy Calibration

The energy of an event is first defined as the sum of the integral of the waveforms from both segment PMTs in ADC units. The next step involves converting to energy units of MeV and correcting for longitudinal light collection variation. These procedures are performed using neutron captures on  ${}^6\text{Li}$  ( $n\text{Li}$ ) because they are well understood and always peak at a quenched energy of around 0.53 MeV electron equivalent (MeVee).

After combining the waveforms for all events, the neutron captures at the center of the segment are calibrated to 0.526 MeVee, defining the energy scale for all segments and all classes of events. Constraining the energy scale in this way creates a quadratic dependence of energy on position, as seen in the left panel of Figure 5.6. This is corrected for by calibrating a gain factor for each PMT using two metrics. The first is the neutron capture signal at cell center,  $S = \sqrt{S_0 S_1}$ , which is found by fitting the distribution in the left panel of Figure 5.6 with a quadratic polynomial. The second is the light ratio,  $R = S_1/S_0$ , at cell center which is found by fitting the distribution in the right panel of Figure 5.6 with a cubic polynomial. The gain factors for both PMTs are then defined as,

$$g_0 = \frac{S}{\sqrt{R} E_n} \quad g_1 = \frac{S \sqrt{R}}{E_n} \quad (5.3)$$

where  $E_n$  is the energy of the neutron capture peak.



**Figure 5.6:** (Left) Neutron capture events in one segment versus  $dt$ , with a quadratic fit in red. (Right) The  $\ln$  signal ratio versus  $dt$  for muon events in one segment, with a cubic polynomial fit in magenta.

## 5.3 Monte Carlo Simulation

Due to the geometry of the PROSPECT detector and properties of the scintillator, reconstructed events are highly position and energy dependent. In order to perform an oscillation analysis it is important to understand the detector response to incoming antineutrino events. This is done by modeling the detector, including all material and scintillator properties, in a GEANT-4 based simulation package hereto referred to as PROSPECT-G4 (PG4). Monte Carlo (MC) simulations with PG4 generate a position-dependent energy response that is used to interpret real physics data. This can only be done if PG4 behaves the same way that the PROSPECT detector does. This is ensured by tuning values in PG4 to reproduce distributions measured by a variety of radioactive calibration sources and intrinsic background energy depositions.

### 5.3.1 Nonlinearity

The nonlinearity of the scintillator response at low energies is parameterized in PG4 using a combination of Birks' quenching model [56] and a Cherenkov radiation model. Birks' law defines the light yield per path length as a function of the energy loss per path length for a particle traveling through scintillator and at each simulation step  $i$  is applied using

$$\frac{dE_{scint}}{dx} = \frac{\frac{dE}{dx}}{1 + k_{B1} \frac{dE}{dx} + k_{B2} \left( \frac{dE}{dx} \right)^2} \quad (5.4)$$

where  $k_{B1}$  and  $k_{B2}$  are the Birks' constants which depend on the material and  $dE/dx$  is the true deposited energy.

Particles traveling faster than the speed of light in the scintillator can emit Cherenkov radiation, therefore, the number of Cherenkov photons,  $N$ , generated at each simulation step is calculated as

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda} \left( 1 - \frac{1}{\beta^2 n^2(\lambda)} \right) \quad (5.5)$$

where  $\alpha$  is the fine structure constant,  $z$  is the particle's electric charge,  $\beta$  is the speed of the particle, and  $n(\lambda)$  is the index of refraction. The energy emitted from the Cherenkov radiation is then calculated as the summed energy of detected Cherenkov

photons,

$$E_c = k_c \sum_{\lambda} N_{\lambda} E_{\lambda} \quad (5.6)$$

where  $k_c$  is the efficiency of detecting Cherenkov light. Comparison between data and MC allows the tuning of both Birks' constants,  $k_{B1}$  and  $k_{B2}$ , and  $k_c$ .

### 5.3.2 Energy Response

Reconstructed energy distributions,  $E_{rec}$ , are measured using a variety of calibration sources placed at z-center positions in the detector. Similar distributions can also be created through MC simulations by setting values for  $k_{B1}$  and  $k_{B2}$ , and  $k_c$  as well as an absolute energy scale factor,  $A$ . A comparison between the data and MC allows for the tuning of these values until good agreement is shown between the two sets of distributions.

For these studies three  $\gamma$ -ray sources were used,  $^{60}\text{Co}$ ,  $^{137}\text{Cs}$ , and  $^{22}\text{Na}$ , along with  $\gamma$ 's resulting from neutron-Hydrogen captures using  $^{252}\text{Cf}$  as the neutron source ( $\gamma$  energies listed in Table 4.1). The spectrum of  $^{12}\text{B}$  was also measured because its  $\beta$  dominated energy distribution (3 MeV to 13.6 MeV) covers a similar energy range as IBD events. As well as comparing the energy spectra,  $^{137}\text{Cs}$  and  $^{22}\text{Na}$  are used to compare event multiplicity between MC and data. The results of these comparisons can be seen in Figure 5.7, where good agreement is seen between MC and data. The best-fit parameters determined by these studies are  $(A, k_{B1}, k_{B2}, k_c) = (1.0026 \pm 0.004, 0.132 \pm 0.004 \text{ MeV/cm}, 0.023 \pm 0.004 \text{ MeV/cm}, 37 \pm 2\%)$ , with a  $\chi^2/\text{ndf}$  of 581.5/420.

Further agreement can be seen when comparing the peak locations for all  $\gamma$ -ray sources as seen in Figure 5.8. The ratio between data and MC is shown to be within  $\pm 1\%$  for all sources for three different time periods.

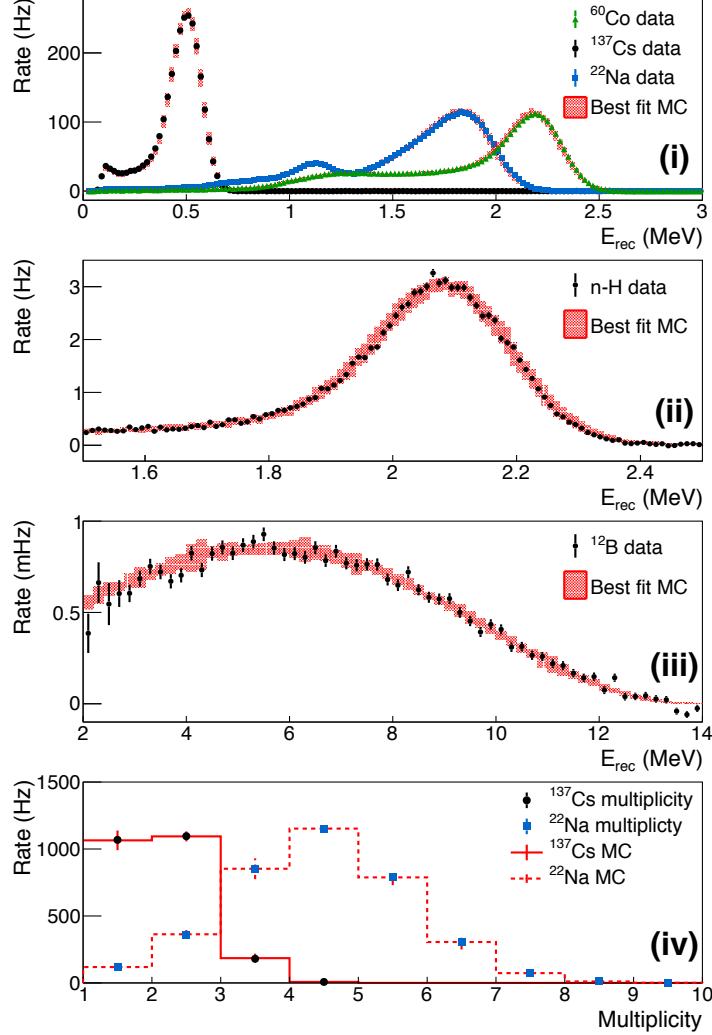
### 5.3.3 Energy Resolution

A comparison of MC and data energy distributions of the  $\gamma$ -ray sources can also be used to define an energy resolution function. MC simulated energy distributions are smeared according to Gaussian distributions until they match data. The resolution of the smeared distributions is then compared to the true deposited energy and fit

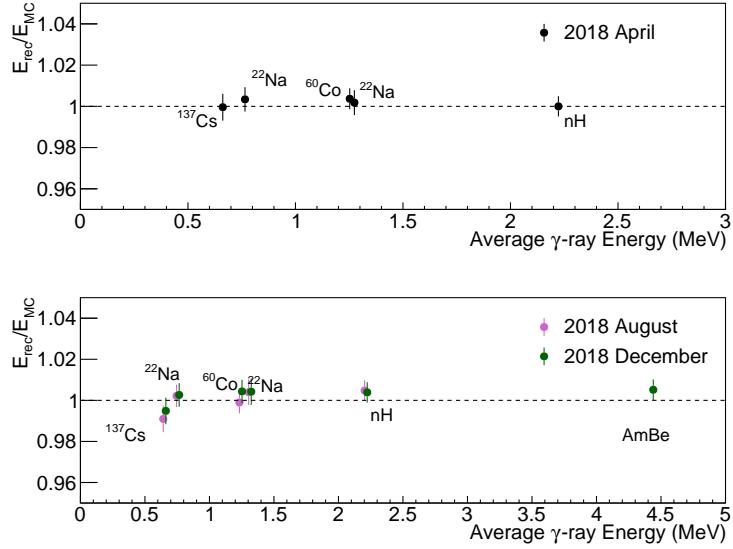
with the function

$$\frac{\sigma_E}{E_{rec}} = \sqrt{a^2 + \frac{b^2}{E_{rec}} + \frac{c^2}{E_{rec}^2}} \quad (5.7)$$

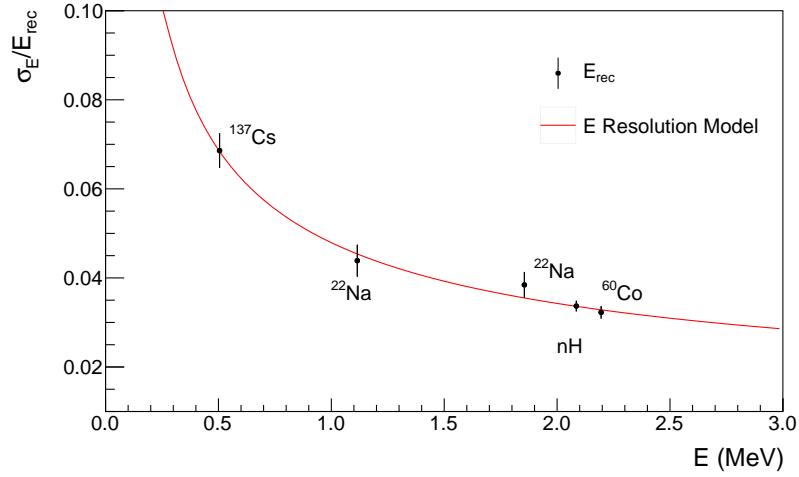
where  $a$ ,  $b$ , and  $c$  are dependent on detector geometry, photostatistics (PE/MeV), and PMT quantum efficiency respectively. The results of this can be seen in Figure 5.9, where the parameters are found to be  $(a, b, c) = (1.15\% \pm 0.47\%, 4.61\% \pm 0.24\%, 0 \pm 1.3\%)$ , resulting in an energy resolution at 1 MeV of  $4.76\% \pm 0.2\%$ .



**Figure 5.7:** Reconstructed energy distributions for calibration data and PG4 Monte Carlo simulations [57]. (i):  $E_{rec}$  for  $\gamma$ -ray source deployments; (ii):  $E_{rec}$  for n-H captures from a  $^{252}\text{Cf}$  source deployment; (iii):  $E_{rec}$  for cosmogenically produced  $^{12}\text{B}$ ; (iv): pulse multiplicity for  $^{137}\text{Cs}$  and  $^{22}\text{Na}$  source deployments. Error bands indicate statistical (data) and systematic (PG4) uncertainties.



**Figure 5.8:** Ratio of data versus PG4 Monte Carlo simulation energy peak locations of the given  $\gamma$  sources, plotted versus true gamma energy for three different time periods [57]. Error bands indicate statistical and systematic uncertainties. Ratios for all datasets are within  $\sim 1\%$  of unity, indicating accurate energy response modeling in PG4 for a wide energy range.



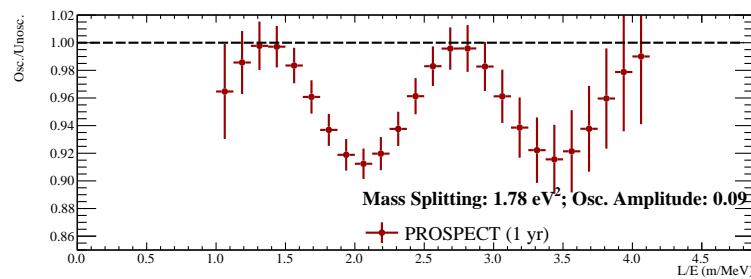
**Figure 5.9:** Energy resolution of PG4 Monte Carlo simulation distributions matched to data versus true gamma energy for the given calibration sources fit with the function in Eq. 5.7 [57]. Error bands indicate statistical and systematic uncertainties.

# CHAPTER 6

## $^{227}\text{AC}$ AS A CALIBRATION SOURCE

### 6.1 Motivation

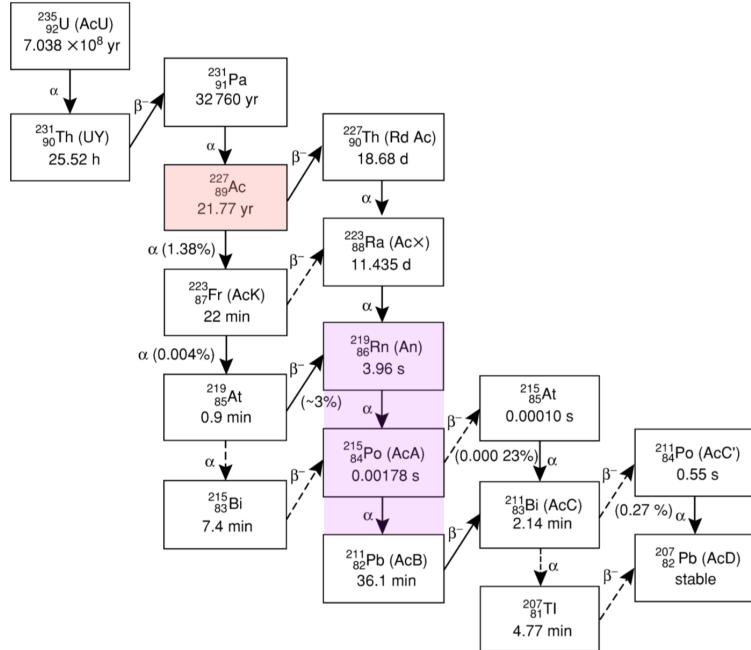
In the absence of an eV-scale sterile neutrino PROSPECT should measure IBD rates that fall like one over distance from the reactor squared. If sterile neutrino oscillation was detected, after one year PROSPECT would measure the spectrum seen in Figure 6.1, given a mass splitting of  $1.78 \text{ eV}^2$ , . However, a situation could occur in which a sterile neutrino did not exist, or could not be measured with PROSPECT, and an oscillation is still measured. This could happen if there are segment to segment volume variations throughout the detector, mimicking an oscillation signal. Therefore, it becomes important that the product of efficiency  $\times$  volume for all segments is well known.



**Figure 6.1:** The ratio of the oscillated to un-oscillated neutrino spectrum as a function of  $L/E$  that would be observed by PROSPECT after 1 year if a sterile neutrino signal was detected [58].

This measurement can be accomplished if an event source is uniformly distributed throughout the active volume of the detector. By measuring the rate of this source in each segment the relative volumes can be compared and tracked through time.  $^{227}\text{Ac}$  was chosen as the source and a chloride solution was prepared and dissolved in the liquid scintillator to ensure uniform distribution.

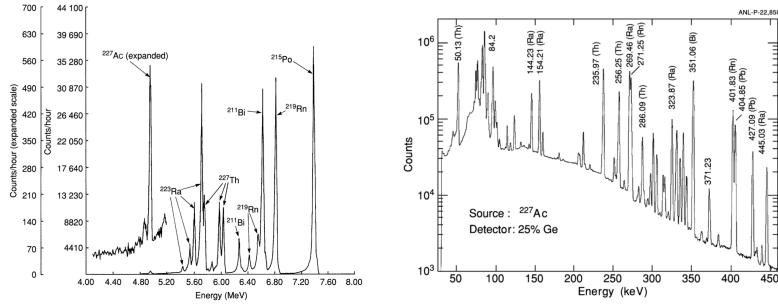
$^{227}\text{Ac}$  was chosen for several reasons. First, because an  $\alpha$ ,  $\alpha$  coincidence occurs in its decay chain, specifically  $^{219}\text{Rn} \rightarrow ^{215}\text{Po} + \alpha \rightarrow ^{211}\text{Pb} + \alpha$ , as highlighted in Figure 6.2.  $^{219}\text{Rn}$  has a half-life of  $3.96 \pm 0.01$  s and  $\alpha$ -decays 100% of the time, while  $^{215}\text{Po}$  has a half-life of  $1.781 \pm 0.005$  ms and  $\alpha$ -decays  $99.99977(2)\%$  of the time, so the  $\alpha$ ,  $\alpha$  coincidences happen frequently and quickly.



**Figure 6.2:** The full decay chain of  $^{227}\text{Ac}$  (a daughter of  $^{235}\text{U}$ ), in which the  $\alpha$ ,  $\alpha$  coincidence of interest is highlighted [59].

	$E_\alpha$ [keV]	$I_\alpha$ %	$E_\gamma$ [keV]	$I_\gamma$ %
$^{219}\text{Rn}$	6425.0(10)	7.5(6)	271.23(1)	10.8(6)
	6530(2)	0.110(10)	401.81(1)	6.6(4)
	6552.6(10)	12.9(6)		
	6819.1(3)	79.4(10)		
$^{215}\text{Po}$	7386.1(8)	99.999770(20)		

**Table 6.1:** Energy and absolute intensity of  $\alpha$  and  $\gamma$  decay radiation for  $^{219}\text{Rn}$  and  $^{215}\text{Po}$ .



**Figure 6.3:** [59]

## 6.2 Material Compatibility

## 6.3 Event Selection in the PROSPECT AD

## 6.4 Detector Stability Results

## 6.5 Volume Variation Results

# CHAPTER 7

## NEUTRINO OSCILLATION IN THE PROSPECT AD

# CHAPTER 8

# CONCLUSIONS

# BIBLIOGRAPHY

- [1] L. Meitner O. von Baeyer, O. Hahn. Über die  $\beta$ -Strahlen des aktiven Niederschlags des Thoriums. *Zeitschrift fur Physik*, 12:273–279, 1911.
- [2] J. Chadwick. The intensity distribution in the magnetic spectrum of beta particles from radium (B + C). *Verh. Phys. Gesell.*, 16:383–391, 1914.
- [3] C. D. Ellis and W. A. Wooster. The average energy of disintegration of radium E. *Proceedings of the Royal Society of London Series A*, 117:109–123, 1927.
- [4] E. Fermi. An attempt of a theory of beta radiation. 1. *Z. Phys.*, 88:161–177, 1934.
- [5] C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire. Detection of the free neutrino: a confirmation. *Science*, 124(3212):103–104, 1956.
- [6] G. Danby, J-M. Gaillard, K. Goulian, L. M. Lederman, N. Mistry, M. Schwartz, and J. Steinberger. Observation of high-energy neutrino reactions and the existence of two kinds of neutrinos. *Phys. Rev. Lett.*, 9:36–44, Jul 1962.
- [7] K. Kodama et al. Observation of tau neutrino interactions. *Phys. Lett.*, B504:218–224, 2001.
- [8] K. Kodama et al. Final tau-neutrino results from the donut experiment. *Phys. Rev. D*, 78:052002, Sep 2008.
- [9] M. Goldhaber, L. Grodzins, and A. W. Sunyar. Helicity of neutrinos. *Phys. Rev.*, 109:1015–1017, Feb 1958.
- [10] M. Tanabashi et al. Review of particle physics. *Phys. Rev. D*, 98:030001, Aug 2018.

- [11] Aldo Serenelli. Alive and well: a short review about standard solar models. *Eur. Phys. J.*, A52(4):78, 2016.
- [12] Raymond Davis, Don S. Harmer, and Kenneth C. Hoffman. Search for neutrinos from the sun. *Phys. Rev. Lett.*, 20:1205–1209, May 1968.
- [13] B. Pontecorvo. Neutrino Experiments and the Problem of Conservation of Leptonic Charge. *Sov. Phys. JETP*, 26:984–988, 1968. [Zh. Eksp. Teor. Fiz.53,1717(1967)].
- [14] S M Bilen’ki and Bruno Pontecorvo. Lepton mixing and neutrino oscillations. *Soviet Physics Uspekhi*, 20(10):776, 1977.
- [15] J. N. Abdurashitov et al. Results from SAGE. *Phys. Lett.*, B328:234–248, 1994.
- [16] W. Hampel et al. GALLEX solar neutrino observations: Results for GALLEX IV. *Phys. Lett.*, B447:127–133, 1999.
- [17] M. Altmann et al. GNO solar neutrino observations: Results for GNO I. *Phys. Lett.*, B490:16–26, 2000.
- [18] E. Bellotti. First results from GNO. *Nucl. Phys. Proc. Suppl.*, 91:44–49, 2001. [,44(2001)].
- [19] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.*, 81:1562–1567, Aug 1998.
- [20] Q. R. Ahmad et al. Measurement of the rate of  $\nu_e + d \rightarrow p + p + e^-$  interactions produced by  $^8b$  solar neutrinos at the sudbury neutrino observatory. *Phys. Rev. Lett.*, 87:071301, Jul 2001.
- [21] Q. R. Ahmad et al. Direct evidence for neutrino flavor transformation from neutral-current interactions in the sudbury neutrino observatory. *Phys. Rev. Lett.*, 89:011301, Jun 2002.
- [22] A. C. Hayes and Petr Vogel. Reactor Neutrino Spectra. *Ann. Rev. Nucl. Part. Sci.*, 66:219–244, 2016.
- [23] NNDC. Chart of Nuclides.

- [24] F. Von Feilitzsch, A. A. Hahn, and K. Schreckenbach. EXPERIMENTAL BETA SPECTRA FROM PU-239 AND U-235 THERMAL NEUTRON FISSION PRODUCTS AND THEIR CORRELATED ANTI-NEUTRINOS SPECTRA. *Phys. Lett.*, 118B:162–166, 1982.
- [25] K. Schreckenbach, G. Colvin, W. Gelletly, and F. Von Feilitzsch. DETERMINATION OF THE ANTI-NEUTRINO SPECTRUM FROM U-235 THERMAL NEUTRON FISSION PRODUCTS UP TO 9.5-MEV. *Phys. Lett.*, 160B:325–330, 1985.
- [26] A. A. Hahn, K. Schreckenbach, G. Colvin, B. Krusche, W. Gelletly, and F. Von Feilitzsch. Anti-neutrino Spectra From  $^{241}\text{Pu}$  and  $^{239}\text{Pu}$  Thermal Neutron Fission Products. *Phys. Lett.*, B218:365–368, 1989.
- [27] N. Haag, A. Gtlein, M. Hofmann, L. Oberauer, W. Potzel, K. Schreckenbach, and F. M. Wagner. Experimental Determination of the Antineutrino Spectrum of the Fission Products of  $^{238}\text{U}$ . *Phys. Rev. Lett.*, 112(12):122501, 2014.
- [28] P. Vogel, G. K. Schenter, F. M. Mann, and R. E. Schenter. Reactor antineutrino spectra and their application to antineutrino-induced reactions. ii. *Phys. Rev. C*, 24:1543–1553, Oct 1981.
- [29] Th. A. Mueller et al. Improved Predictions of Reactor Antineutrino Spectra. *Phys. Rev.*, C83:054615, 2011.
- [30] Patrick Huber. On the determination of anti-neutrino spectra from nuclear reactors. *Phys. Rev.*, C84:024617, 2011. [Erratum: Phys. Rev.C85,029901(2012)].
- [31] Xin Qian and Jen-Chieh Peng. Physics with Reactor Neutrinos. *Rept. Prog. Phys.*, 82(3):036201, 2019.
- [32] F. P. An et al. The Detector System of The Daya Bay Reactor Neutrino Experiment. *Nucl. Instrum. Meth.*, A811:133–161, 2016.
- [33] Feng Peng An et al. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay. *Phys. Rev. Lett.*, 116(6):061801, 2016. [Erratum: Phys. Rev. Lett.118,no.9,099902(2017)].

- [34] D. Adey et al. Improved Measurement of the Reactor Antineutrino Flux at Daya Bay. 2018. arXiv:1808.10836 [hep-ex].
- [35] K. N. Abazajian et al. Light Sterile Neutrinos: A White Paper. 2012.
- [36] A. Aguilar-Arevalo et al. Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam. *Phys. Rev.*, D64:112007, 2001.
- [37] A. A. Aguilar-Arevalo et al. Improved Search for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  Oscillations in the MiniBooNE Experiment. *Phys. Rev. Lett.*, 110:161801, 2013.
- [38] Carlo Giunti and Marco Laveder. Statistical Significance of the Gallium Anomaly. *Phys. Rev.*, C83:065504, 2011.
- [39] G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, and A. Letourneau. The Reactor Antineutrino Anomaly. *Phys. Rev.*, D83:073006, 2011.
- [40] S. H. Seo et al. Spectral Measurement of the Electron Antineutrino Oscillation Amplitude and Frequency using 500 Live Days of RENO Data. *Phys. Rev.*, D98(1):012002, 2018.
- [41] H. De Kerret et al. First Double Chooz  $\theta_{13}$  Measurement via Total Neutron Capture Detection. 2019. arXiv:1901.09445 [hep-ex].
- [42] J. Ashenfelter et al. The PROSPECT Reactor Antineutrino Experiment. *Nucl. Instrum. Meth.*, A922:287–309, 2019.
- [43] J. Ashenfelter et al. First Search for Short-Baseline Neutrino Oscillations at HFIR with PROSPECT. *Phys. Rev. Lett.*, 121:251802, Dec 2018.
- [44] J. Ashenfelter et al. Measurement of the Antineutrino Spectrum from  $^{235}\text{U}$  Fission at HFIR with PROSPECT. *Phys. Rev. Lett.*, 122(25):251801, 2019.
- [45] Germina Ilas, David Chandler, Brian Ade, Eva Sunny, Ben Betzler, and Dan Pinkston. Modeling and simulations for the high flux isotope reactor cycle 400. Technical report, Oak Ridge National Laboratory, 3 2015. <https://info.ornl.gov/sites/publications/Files/Pub54181.pdf>.

- [46] J. Ashenfelter et al. Background Radiation Measurements at High Power Research Reactors. *Nucl. Instrum. Meth.*, A806:401–419, 2016.
- [47] Blaine Alexander Heffron. Characterization of Reactor Background Radiation at HFIR for the PROSPECT Experiment. [https://trace.tennessee.edu/utk\\_gradthes/4747/](https://trace.tennessee.edu/utk_gradthes/4747/).
- [48] Brennan Hackett. DANG and the Background Characterisation of HFIR for PROSPECT. [https://prospect.yale.edu/sites/default/files/hackett\\_brennan\\_university\\_of\\_surrey.pdf](https://prospect.yale.edu/sites/default/files/hackett_brennan_university_of_surrey.pdf).
- [49] J. Ashenfelter et al. A Low Mass Optical Grid for the PROSPECT Reactor Antineutrino Detector. *JINST*, 14(04):P04014, 2019.
- [50] J. Ashenfelter et al. The Radioactive Source Calibration System of the PROSPECT Reactor Antineutrino Detector. *Nucl. Instrum. Meth.*, A944:2019, 2019.
- [51] J. Ashenfelter et al. Lithium-loaded Liquid Scintillator Production for the PROSPECT experiment. *JINST*, 14(03):P03026, 2019.
- [52] M. Mendenhall. PRD Figure 3a: average pulse shapes. PROSPECT DocDB 2773-v1, May 2019.
- [53] M. Mendenhall. PRD Figure 4: pulse analysis. PROSPECT DocDB 2764-v4, May 2019.
- [54] M. Mendenhall. PRD Figure 7: PSD vs Signal. PROSPECT DocDB 2731-v1, May 2019.
- [55] M. Mendenhall. AD1 Calibrations tech note. PROSPECT DocDB 2314-v2, May 2018.
- [56] J.B. BIRKS. Chapter 8 - organic liquid scintillators. In J.B. BIRKS, editor, *The Theory and Practice of Scintillation Counting*, International Series of Monographs in Electronics and Instrumentation, pages 269 – 320. Pergamon, 1964.
- [57] Xianyi Zhang. E Scale Tech Note for PRD Analysis. PROSPECT DocDB 2815-v1, July 2019.

- [58] Pranava Surukuchi. Sensitivity public talks. PROSPECT DocDB 1534-v9, August 2017.
- [59] H. W. Kirby and L. R. Morss. Actinium. In L. R. Morss, N. M. Edelstein, and J. Fuger, editors, *The Chemistry of the Actinide and Transactinide Elements*, chapter 2, pages 18–51. Springer, 2011.

# **APPENDIX A**

## **SOME ADDITIONAL STUFF**

Appendices go at the end.

# **APPENDIX B**

## **MORE ADDITIONAL STUFF**

This is another appendix.