

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

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# 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.

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# **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 the laws of conservation 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]:

$$\bar{\nu} + p \rightarrow n + e^+ \tag{2.1}$$

Their idea was to place a detector near a generated flux 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 neutrino flux large enough to provide 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 neutrino,  $\nu_\tau$ , by the DONUT (Direct Observation of the Nu Tau) experiment would not occur until 44 years later [7, 8].

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

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

## 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 permanent 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,  $\nu_\alpha$ :  $\alpha = e, \mu, \tau$ , where each flavor is a superposition of mass eigenstates,  $\nu_i$ :  $i = 1, 2, 3$ :

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

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

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

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

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

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

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

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

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

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, astrophysicists Raymond Davis and John Bahcall 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

$$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^- \quad (2.13)$$

in which a neutrino would enter the tank and transform chlorine into argon, which he would then extract and count. 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 [10]. 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 [11, 12].

Several experiments designed to calculate the flux of solar neutrinos followed the Homestake Experiment including SAGE [13], GALLEX [14], and GNO [15, 16]. All three experiments built detectors based on the reaction  ${}^{71}\text{Ga}(\nu, e^-){}^{71}\text{Ge}$ , and all three experiments showed a deficit in neutrino flux compared to Standard Model calculations.

Further experimental proof of neutrino oscillation came with results from the Super-Kamiokande Experiment. Unlike previous experiments that were only sensi-

Parameter	Best-fit	$3\sigma$
$\Delta m_{21}^2$ [ $10^{-5}$ eV <sup>2</sup> ]	7.37	6.93 - 7.96
$\Delta m_{31(23)}^2$ [ $10^{-3}$ 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 [20]. The values (values in brackets) correspond to  $m_1 < m_2 < m_3$  ( $m_3 < m_1 < m_2$ ).

tive to electron neutrinos, Super-K detected neutrinos through elastic scattering of electrons - a process sensitive to all neutrino flavors. 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 [17].

The first direct evidence for solar neutrino flavor change came from the Sudbury Neutrino Observatory (SNO) in 2001 [18, 19]. 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, and the  $\nu_x - d$  neutral current interaction) that, combined, were sensitive to all three neutrino flavors.

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.

# CHAPTER 3

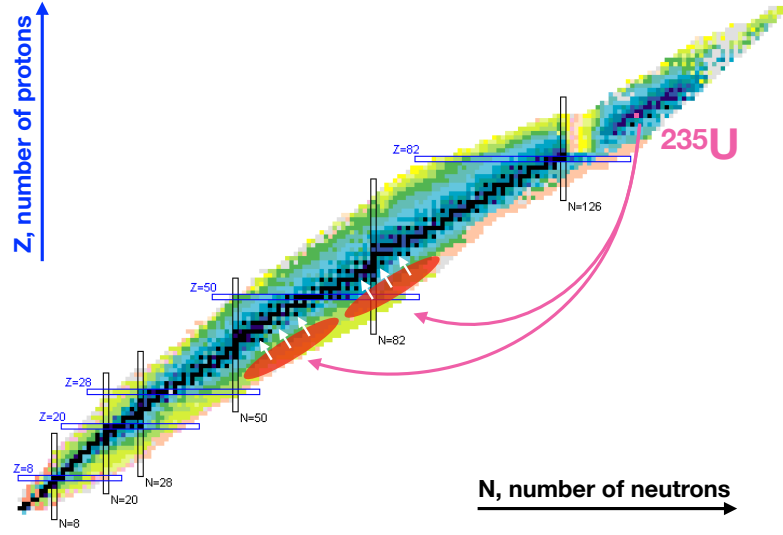
## REACTOR NEUTRINOS

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 chain 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 only 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 [21].





**Figure 3.1:** A schematic of the fission of  $^{235}\text{U}$  [22]. 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

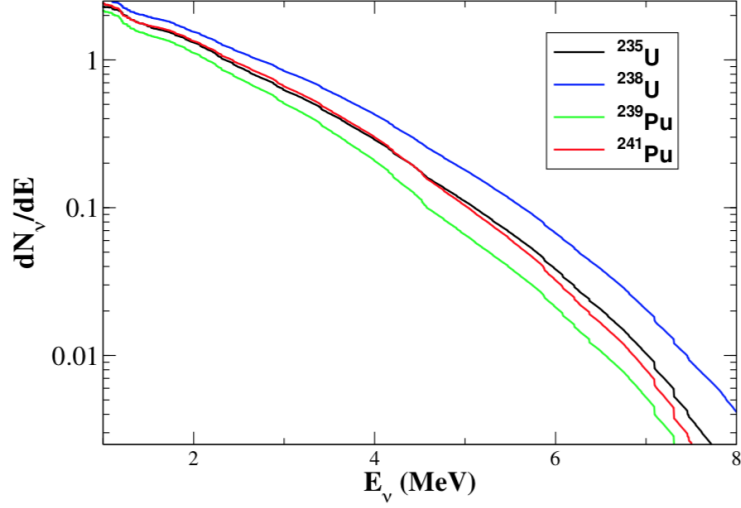
The total  $\bar{\nu}_e$  flux,  $S(E_\nu)$ , produced by a nuclear reactor can be expressed as the sum over the spectra of the dominant fissioning isotopes,

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

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 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,

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



**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 [21].

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. [21] and the result can be seen in Figure 3.2.

Though seemingly straightforward, this approach comes with some caveats. The sheer 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 [23, 24, 25], while the spectrum of  $^{238}\text{U}$  was more recently (2014) measured at the neutron source FRMII in Garching, Germany [26]. The ILL measurements, along with a prediction of the  $^{238}\text{U}$   $\bar{\nu}_e$  spectrum using the summation method by Vogel [27], 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 [28]. 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 [29].

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.[21]. Besides the model uncertainties there are also experimental uncertainties that come from knowing the thermal power of the reactor, its time-dependent fuel composition, and the fission energies of the dominant isotopes. All of this results in a 10-20% relative uncertainty on the reactor antineutrino spectra using the *ab initio* method and  $\sim 5\%$  uncertainty on the conversion approach [30].

### 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 [30], and can be written as

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

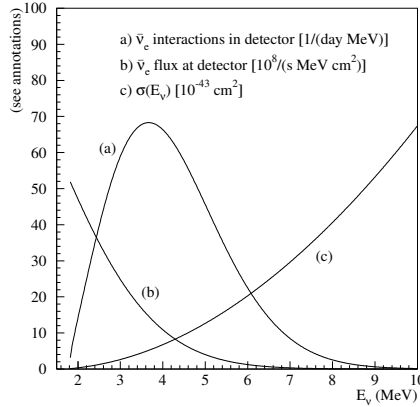
where  $E_e$  and  $p_e$  are the energy and momentum of the final-state positron.

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 neutron energy can be backtracked from the prompt signal as

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

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.

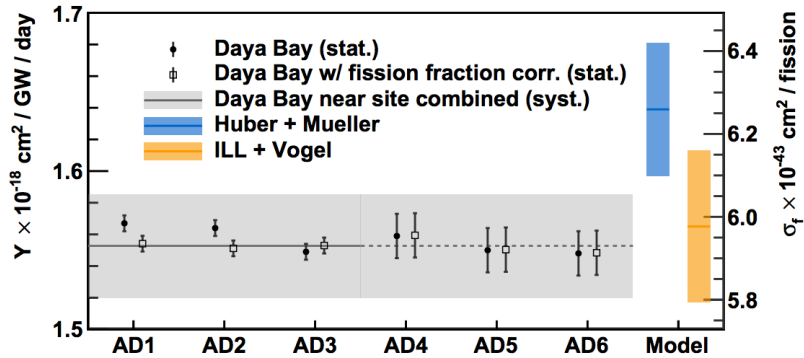


**Figure 3.3:** The IBD spectrum (curve (a)) measured by a 12-ton fiducial mass detector located 0.8 km from a 12-GW<sub>th</sub> power reactor along with the reactor flux (curve (b)) and IBD cross section (curve (c)) as a function of energy [20].

### 3.4 The Reactor Antineutrino Anomaly

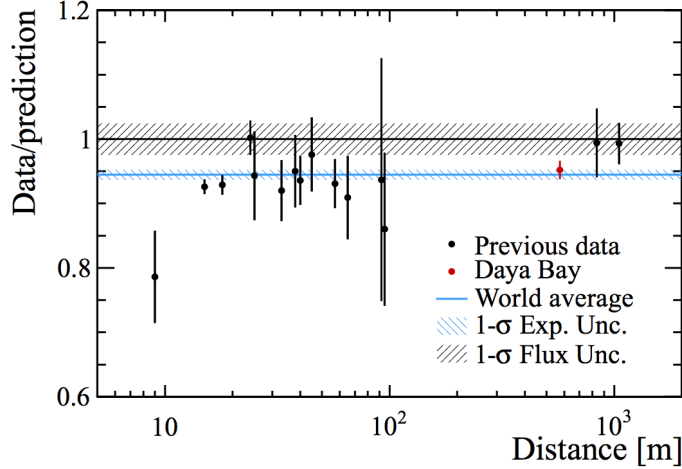
Several experiments have, and continue to use reactor antineutrinos as a probe of neutrino oscillation. A reactor neutrino disappearance  $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$  experiment located at a distance  $L \sim 1$  km can measure  $\sin^2 \Delta_{31}$ . At that baseline, the amplitude of the oscillation at the first maximum of  $\sin^2 \Delta_{31}$  is  $\sin^2 2\theta_{13}$ , 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 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 [31, 32]. 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.



**Figure 3.4:** Rate of reactor antineutrino candidate events in Daya Bay’s six detectors [32]. 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.

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

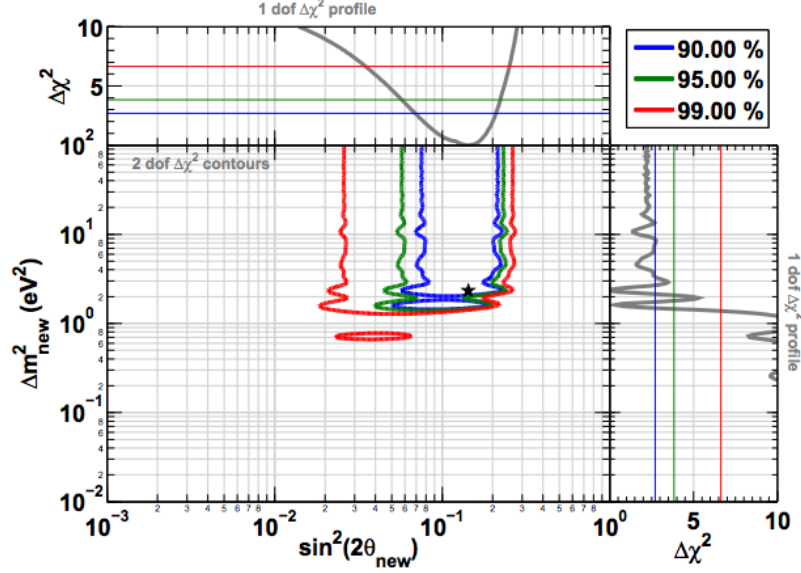


**Figure 3.5:** The measured reactor  $\bar{\nu}_e$  rate, normalized to the Huber+Mueller model prediction, as a function of distance from the reactor [33]. The rate is corrected for 3-flavor neutrino oscillations at each baseline. The blue shaded region represents the global average and its  $1\sigma$  uncertainty. The  $2.7\sigma$  model uncertainty is shown as a band around unity.

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 [33]. 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 [21]. Thus labeling this predicament as the “reactor antineutrino anomaly” (RAA).

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 [34]. 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 [35] along with excesses measured by the Mini Booster Neutrino Experiment (MiniBooNE) of  $\nu_e$  ( $3.4\sigma$ ) and  $\bar{\nu}_e$  ( $2.8\sigma$ ) [36]. 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  $3\sigma$  [37].

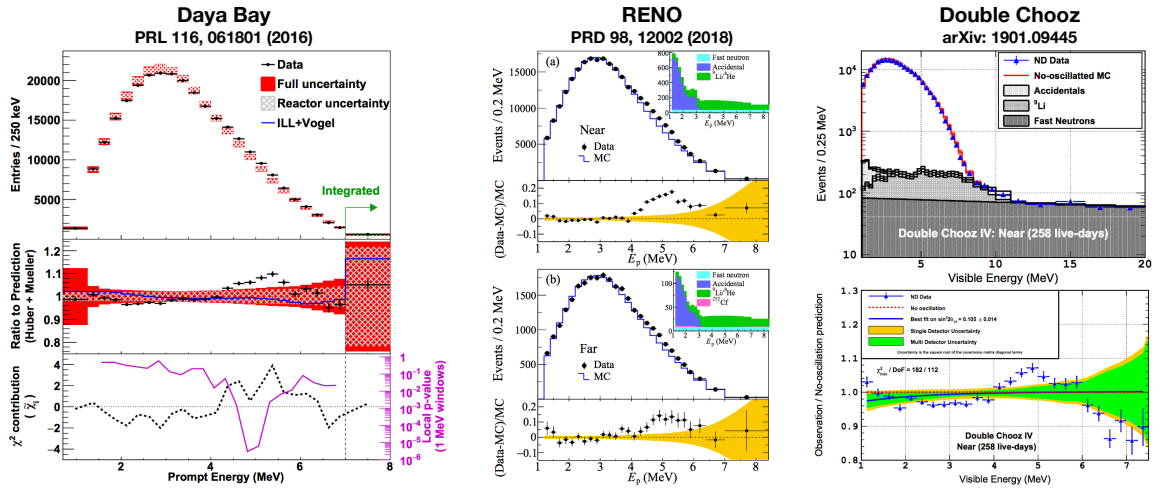
All of these anomalies hint at short-baseline oscillations of electron neutrinos. The simplest way to explain these discrepancies is to add onto the standard model



**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  $\sin^2(2\theta_{14}) = 0.14 \pm 0.08$  [38].

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 [38].

An alternative explanation is that the flux predictions are incorrect and have larger uncertainties than is currently applied. The idea that the calculated reactor antineutrino flux is not well understood is bolstered by results from Daya Bay [32], RENO [39], and Double Chooz [40] in which a “bump” was observed in the experimentally measured antineutrino energy spectrum relative to the model spectrum, shown in Figure 3.7.



**Figure 3.7:** A comparison between the predicted and measured prompt energy spectra of IBD events in Daya Bay [32], RENO [39], and Double Chooz [40]. All experiments observe an excess of events above uncertainty in the model spectrum in the 4-6 MeV region.



# 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. 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.[41, 42].

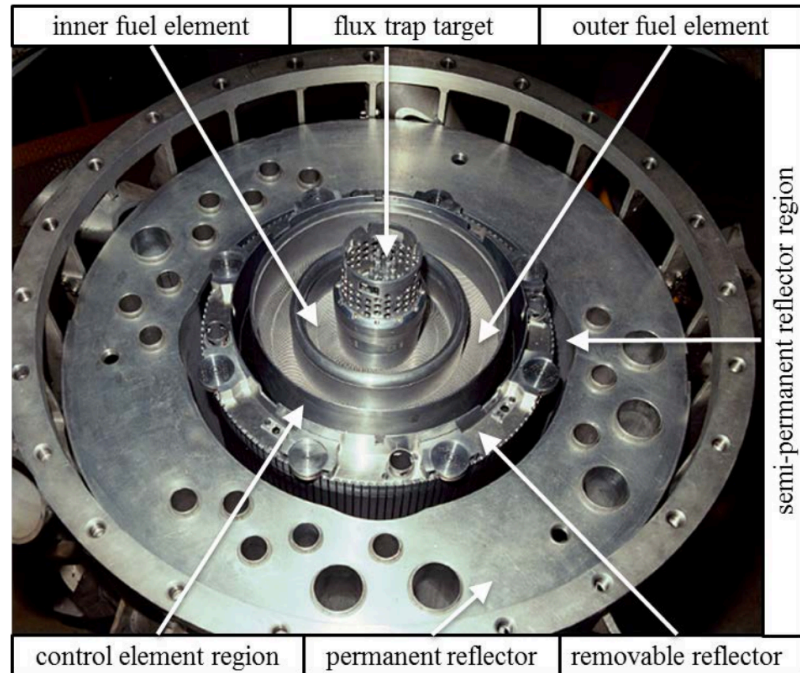


Figure 4.1: [43]

## 4.1 HFIR

## 4.2 Design

## 4.3 Detecting Inverse Beta Decays

## 4.4 From Signal to Result

# CHAPTER 5

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

5.1 Motivation

5.2 Material Compatibility

5.3 Prototype Testing in P50X

5.4 Event Selection in the PROSPECT AD

5.5 Detector Stability Results

5.6 Volume Variation Results

# **CHAPTER 6**

## **INVERSE BETA DECAY EVENT SELECTION**

- 6.1 Selection Criteria and Efficiency**
- 6.2 Properties of the Event Selection**

# CHAPTER 7

## NEUTRINO OSCILLATION IN THE PROSPECT AD

7.1 Analysis Method

7.2 Result

# CHAPTER 8

## CONCLUSIONS

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# **APPENDIX A**

## **SOME ADDITIONAL STUFF**

Appendices go at the end.

# **APPENDIX B**

## **MORE ADDITIONAL STUFF**

This is another appendix.