

A Search for Shot-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:

"Name of Advisor", Department of Physics, Advisory chair

"Name of thesis committee chair", Department of Physics

"Reader", Department of Physics

"External Reader", External Member, "Reader's Institution"

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}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 ^6Li -loaded liquid scintillator. Due to characteristics of its decay chain, ^{227}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}Ac decay chain we can measure the rate of ^{227}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.

CONTENTS

ABSTRACT	i
LIST OF FIGURES	iv
LIST OF TABLES	v
1 INTRODUCTION	1
2 Neutrinos	2
2.1 Discovery of the Neutrino	2
2.2 Neutrinos in the Standard Model	4
2.3 Lepton Mixing	4
2.4 Neutrino Oscillation	4
2.5 Discovery of Neutrino Oscillation	4
3 Reactor Neutrinos	5
3.1 Production of Reactor Neutrinos	5
3.2 Measuring the Reactor Antineutrino Flux and Spectrum	5
3.3 The Reactor Antineutrino Anomaly	5
4 Sterile Neutrinos	6
4.1 Theory of Sterile Neutrinos	6
4.2 Experimental Searches for Sterile Neutrinos	6
5 PROSPECT	7
5.1 Motivation	7
5.2 Experimental Site	7
5.3 Design	7

5.4	Detecting Inverse Beta Decays	7
5.5	From Signal to Result	7
6	^{227}Ac as a Calibration Source	8
6.1	Motivation	8
6.2	Material Compatibility	8
6.3	Prototype Testing in P50X	8
6.4	Event Selection in the PROSPECT AD	8
6.5	Detector Stability Results	8
6.6	Volume Variation Results	8
7	Inverse Beta Decay Event Selection	9
7.1	Selection Criteria and Efficiency	9
7.2	Properties of the Event Selection	9
8	Neutrino Oscillation in the PROSPECT AD	10
8.1	Analysis Method	10
8.2	Result	10
9	CONCLUSIONS	11
	REFERENCES	12

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

CHAPTER 2

Neutrinos

2.1 Discovery of the Neutrino

The study of radioactive decay in the early 20th century brought to light discrepancies that would lead to the postulation of the neutrino and later on its discovery. 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. 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, 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, it would take another 20 years until it was discovered experimentally.

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

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

The 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. Any source that generates neutrinos, though, is going to create large backgrounds for your experiment. As would become the game for every neutrino detector after them, 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 m away from a fission bomb. This would create a large enough neutrino flux for 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 them to use a nuclear reactor rather than a fission bomb, giving them the chance to patiently watch for neutrinos rather than have 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.

Neutrinos from the reactor would 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. While this is happening the neutron from the initial reaction is bouncing around as it collides with protons until, eventually, it captures on a cadmium nucleus and releases about a 9 MeV gamma ray, causing the liquid to again scintillate. The time between the flash of light from the positron and that of the neutron is on the order of microseconds. By looking for this delayed-coincidence signature Cowan and Reines were able to successfully detect the first neutrino and paved the way for future neutrino experiments.

Shortly after, in 1962, Lederman, Schwartz, and Steinberger discovered the muon neutrino, ν_μ [6], but it would take until 2000 for the DONUT (Direct Observation of the Nu Tau) experiment to discover the tau neutrino, ν_τ [7, 8].

2.2 Neutrinos in the Standard Model

2.3 Lepton Mixing

2.4 Neutrino Oscillation

2.5 Discovery of Neutrino Oscillation

CHAPTER 3

Reactor Neutrinos

3.1 Production of Reactor Neutrinos

3.2 Measuring the Reactor Antineutrino Flux and Spectrum

3.3 The Reactor Antineutrino Anomaly

CHAPTER 4

Sterile Neutrinos

4.1 Theory of Sterile Neutrinos

4.2 Experimental Searches for Sterile Neutrinos

CHAPTER 5

PROSPECT

5.1 Motivation

5.2 Experimental Site

5.3 Design

5.4 Detecting Inverse Beta Decays

5.5 From Signal to Result

CHAPTER 6

^{227}Ac as a Calibration Source

6.1 Motivation

6.2 Material Compatibility

6.3 Prototype Testing in P50X

6.4 Event Selection in the PROSPECT AD

6.5 Detector Stability Results

6.6 Volume Variation Results

CHAPTER 7

Inverse Beta Decay Event Selection

7.1 Selection Criteria and Efficiency

7.2 Properties of the Event Selection

CHAPTER 8

Neutrino Oscillation in the PROSPECT AD

8.1 Analysis Method

8.2 Result

CHAPTER 9

CONCLUSIONS

REFERENCES

- [1] L. M. O von Baeyer, O Hahn, Zeitschrift fur Physik **12**, 273 (1911).
- [2] J. Chadwick, Verh. Phys. Gesell. **16**, 383 (1914).
- [3] C. D. Ellis and W. A. Wooster, Proceedings of the Royal Society of London Series A **117**, 109 (1927), URL <https://royalsocietypublishing.org/doi/abs/10.1098/rspa.1927.0168>.
- [4] E. Fermi, Z. Phys. **88**, 161 (1934).
- [5] C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire, Science **124**, 103 (1956), ISSN 0036-8075, <http://science.sciencemag.org/content/124/3212/103.full.pdf>, URL <http://science.sciencemag.org/content/124/3212/103>.
- [6] G. Danby, J.-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, and J. Steinberger, Phys. Rev. Lett. **9**, 36 (1962), URL <https://link.aps.org/doi/10.1103/PhysRevLett.9.36>.
- [7] K. Kodama et al. (DONUT), Phys. Lett. **B504**, 218 (2001), hep-ex/0012035.
- [8] K. Kodama et al. (DONuT Collaboration), Phys. Rev. D **78**, 052002 (2008), URL <https://link.aps.org/doi/10.1103/PhysRevD.78.052002>.