

# A Search for Sterile Neutrinos at the NO $\nu$ A Far Detector

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## A Search for Sterile Neutrinos at the NO $\nu$ A Far Detector

### ABSTRACT

We measured things. And searched for other things. Here is what we found, please let me graduate.

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THIS IS THE DEDICATION.



# Acknowledgments

These people were cool.

# 1

## A Brief History of Neutrinos

### 1.1 INTRODUCTION

The neutrino was first postulated by Wolfgang Pauli as a possible explanation for the continuous spectrum of electrons emitted from nuclear  $\beta$  decay [1]. This decay was originally thought to be the emission of an electron from an atom, resulting in a different nucleus, via the process,

$$N \rightarrow N' + e \tag{1.1}$$

where  $N$  and  $N'$  are the parent and daughter nuclei, respectively. In a two body decay such as this, the momenta and energies of the outgoing particles are exactly constrained. Pauli's new particle explained the continuous spectrum of electron energy via a modified decay process:

$$N \rightarrow N' + e + \nu \tag{1.2}$$

where  $\nu$  is the outgoing neutral particle. Pauli's original proposal called the new particle the neutron, but this name was later used to name the massive neutral nucleon discovered by Chadwick in 1932 [2]. Three years after Pauli's idea, Fermi proposed a model for nuclear  $\beta$  decay that included the new particle, which he coined the neutrino, or little neutral one [3].

## 1.2 FIRST DETECTION OF NEUTRINOS

Twenty years passed from Fermi's model proposal before neutrinos were discovered experimentally. Fred Reines and Clyde Cowan made the discovery by placing a detector near a nuclear reactor as a source of neutrinos and observing inverse  $\beta$  decay [4, 5]. The neutrinos observed were anti-electron neutrinos, thus the following was the observed process.

$$p + \bar{\nu}_e \rightarrow n + e^+ \tag{1.3}$$

Reines earned the Nobel Prize in Physics in 1995 for the detection of the neutrino.

In 1962, the muon neutrino was discovered at Brookhaven National Laboratory using the first neutrino beam [6] in a scheme still used in neutrino experiments today. The beam was generated by colliding protons with a target, producing pions that decayed into muons and muon neutrinos. The resultant beam then passed through thick steel, absorbing everything but the neutrinos. Leon Lederman, Melvin Schwartz, and Jack Steinberger won the Nobel Prize in Physics in 1988 for the discovery of the muon neutrino.

The last generation of neutrino, the tau neutrino, was discovered at Fermilab by the DONUT collaboration in 2000 [7].

## 1.3 EVIDENCE OF NEUTRINO OSCILLATIONS

Pontecorvo first postulated neutrino oscillations between neutrinos and anti-neutrinos, analogous to  $K^0/\bar{K}^0$  oscillations, in 1957 [8]. Nothing came of the proposal immediately, but the idea was later revived and modified to solve the solar neutrino problem. The physics community initially viewed neutrino oscillations with skepticism and believed the experiments to be flawed, but over time oscillations

have become an unmistakable and accepted phenomenon.

The solar neutrino problem was born from a large discrepancy between the theoretical and observed number of neutrinos produced by the sun. Neutrinos were used as a study for solar models because photons take a thousand years to escape the dense nuclear plasma to the surface of the sun, but neutrinos are unimpeded. The models, which have been confirmed today, describe a somewhat complicated chain of nuclear reactions, many of which produce neutrinos. Each individual process contributes a neutrinos in a different energy spectrum, but all of the neutrinos are created as electron neutrinos.

The experimental observations and theoretical predictions were both published in 1968. Ray Davis designed an experiment underground in the South Dakota Homestake mine consisting of a tank of an ultra pure chlorine cleaning solution capable of neutrino capture via the process



The argon atoms could be collected and counted for a direct measurement of the neutrino flux [9]. Meanwhile, John Bahcall precisely calculated the expected neutrino flux [10], and the observed rate was found to be about one third of the predicted rate. Pontecorvo revived his theory with the modification of allowing  $\nu_e$  to  $\nu_\mu$  oscillations [11], but the idea was still not taken seriously and it was another 20 years before the solar neutrino problem was confirmed.

#### 1.4 POSSIBLE EVIDENCE OF STERILE NEUTRINOS

There exists some evidence of more than three neutrinos, but the number of active neutrinos is constrained by measurements of the width of the Z boson. LEP has measured the number of active neutrinos to be  $2.984 \pm 0.008$  [12], so the discoveries of the  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$  leave no room for new active neutrinos. (Strictly speaking, there could be other active neutrinos if they had mass greater than half the mass of the Z boson so the Z could not decay to them, but the evidence that does exist suggests a mass splitting from the other neutrino states much smaller than this.)

# 2

## Theory of Neutrino Oscillations

2.1 STANDARD 3-FLAVOR OSCILLATIONS

2.2 MATTER EFFECTS

2.3 STERILE NEUTRINOS

2.4 CURRENT MEASUREMENTS

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## The NO $\nu$ A Experiment

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#### 3.3.1 NEAR DETECTOR

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## Analysis Results and Systematic Errors

8.1 FITTING METHOD

8.2 SYSTEMATIC ERRORS

8.3 RESULTS

# 9

## Conclusions and Future Improvements

### 9.1 CONCLUSIONS

The results of this analysis are consistent with no sterile neutrinos.

### 9.2 FUTURE IMPROVEMENTS

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