A Search for Sterile Neutrinos at the NOνA Far Detector

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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 β 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 ν 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 β 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 β 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

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- \tag{1.4}$$

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 ν_e to ν_μ oscillations [11], but the idea was still not taken seriously and it was another 20 years before the solar neutrino problem was confirmed.

Beginning in 1989, multiple experiments with different methodologies confirmed the solar neutrino problem. Kamiokande, a water Cherenkov detector, measured a rate deficit in 1989 [12]. Two experiments measured solar neutrinos via the reaction

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- \tag{1.5}$$

and measured a similar deficit, SAGE in 1991 [13] and GALLEX in 1992 [14]. With results from three different experimental methods all showing similar rate deficits, the solar neutrino problem could no longer be relegated to an experimental error.

Evidence soon emerged for oscillations with atmospheric neutrinos as well. These neutrinos are produced when cosmic rays collide with particles in the atmosphere and decay, predominantly via the following channels.

$$\begin{aligned}
\pi^{+/-} &\rightarrow \mu^{+/-} + \nu_\mu/\bar{\nu}_\mu \\
\mu^{+/-} &\rightarrow e^{+/-} + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu
\end{aligned} \tag{1.6}$$

Thus, the expected ratio of muon family neutrinos to muon family neutrinos was expected to be 2. Kamiokande measured this ratio in 1992 and found the ratio to be much closer to 1 [15]. Furthermore, the ratio seemed to be dependent on zenith angle, with the measurement being nearly 2 for neutrinos coming from directly overhead, and dropping as the angle increased. Super-Kamiokande (or Super-K), the successor to Kamiokande, improved upon this measurement in 1998 [16], providing the most definitive evidence of neutrino oscillations to that point.

A resolution to the solar neutrino problem did not have to wait much longer with detector technologies capable of discerning different neutrino interaction types. In 2001

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 ± 0.008 [17], so the discoveries of the ν_e, ν_μ, and ν_τ 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.)

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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 NOνA Experiment

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8.3 Results

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Conclusions and Future Improvements

9.1 Conclusions

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

9.2 Future Improvements

References

[1] W. Pauli. Letter to a physicists' gathering at tubingen, 1930.

[2] J. Chadwick. Possible existence of a neutron. *Nature*, 192:312, 1932.

[3] E. Fermi. Versuch einer theorie der β-strahlen. *Zeitschrift für Physik*, 88:161–177, 1934.

[4] F. Reines and C. L. Cowan. Detection of the free neutrino. *Physical Review*, 92:830–831, 1953.

[5] C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire. Detection of the free neutrino: A confirmation. *Science*, 124:103–104, 1956.

[6] G. Danby et al. Observation of high-energy neutrino reactions and the existence of two kinds of neutrinos. *Physical Review Letters*, 9:36–44, 1962.

[7] DONUT Collaboration, K. Kodama et al. Observation of tau neutrino interactions. *Physics Letters B*, 504:218–224, 2001.

[8] B. Pontecorvo. Mesonium and anti-mesonium. *Soviet Journal of Experimental and Theoretical Physics*, 6:429, 1957.

[9] R. Davis, Jr., D. S. Harmer, and K. C. Hoffman. Search for neutrinos from the sun. *Physical Review Letters*, 20:1205–1209, 1968.

[10] J. N. Bahcall, N. A. Bahcall, and G. Shaviv. Present status of the theoretical predictions for the ^{37}cl solar-neutrino experiment. *Physical Review Letters*, 20:1209–1212, 1968.

[11] V. Gribov and B. Pontecorvo. Neutrino astronomy and lepton charge. *Physics Letters B*, 28:493–496, 1969.

[12] K.S. Hirata et al. Observation of b-8 solar neutrinos in the kamiokande-ii detector. *Physical Review Letters*, 63:16–19, 1989.

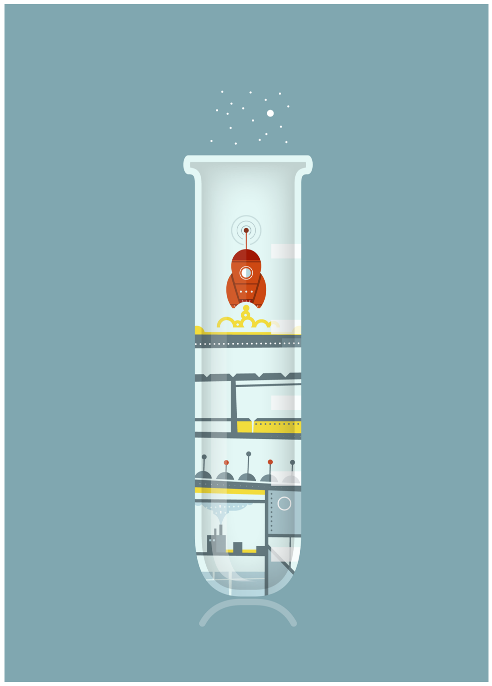
[13] A. I. Abazov et al. Search for neutrinos from the sun using the reaction ^{71}ga (nu$_e$, e$^-$) ^{71}ge. *Physical Review Letters*, 67:3332–3335, 1991.

[14] P. Anselmann et al. Solar neutrinos observed by gallex at gran sasso. *Physics Letters B*, 285:376–389, 1992.

[15] K.S. Hirata et al. Observation of a small atmospheric numu/nue ratio in kamiokande. *Physical Letters B*, 280:146–152, 1992.

[16] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Physical Review Letters*, 81:1562–1567, 1998.

[17] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SID Collaboration, LEP Electroweak Working Group, SID Electroweak Group, Heavy Flavour Group. Precision electroweak measurements on the Z resonance. *Physics Reports*, 427:218–224, 2006.



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