A Search for Shot-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}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}Li-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}Rn $\rightarrow$ ^{215}Po $\rightarrow$ ^{211}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.

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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 [2]. 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 [3] and Ellis and Wooster in 1927 [4].

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" [5]. 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 [6]. 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 [7], but it would take until 2000 for the DONUT (Direct Observation of the Nu Tau) experiment to discover the tau neutrino, ν_τ [8, 9].

2.2 Neutrinos in the Standard Model and Beyond

The Standard Model (SM) of particle physics is the result of the work of many scientists over several decades. It is a field theory that describes three of the four fundamental forces,

	Fermions spin = 1/2				**Bosons** spin = 1	spin = 0
Generation	I	II	III		Gauge Bosons	Scalar Bosons
Quarks	u	c	t		g	H
	d	s	b		γ	
Leptons	e	μ	τ		Z	
	ν_e	ν_μ	ν_τ		W	

Table 2.1: The Standard Model of particle physics.

the electromagnetic, strong and weak forces, and classifies all known elementary particles as outlined in Table 2.1.

Classified as leptons, neutrinos exist in three flavors, electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ), that correspond to the electron (e), muon (μ), and tau (τ) leptons. For each there exists a corresponding antiparticle, $\bar{\nu_e}, \bar{\nu_\mu}, \bar{\nu_\tau}$.

If neutrinos have exactly zero mass and travel at the speed of light, then their helicity, or handedness, is a permanent property. Since experiments had only measured left-handed neutrinos [10], it was assumed that all neutrinos in the SM were massless. As discussed in greater depth in Section 2.3, it was later discovered that neutrinos oscillate, 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, ν_α: $\alpha = e, \mu, \tau$, where each is a superposition of mass eigenstates, ν_i: $i = 1, 2, 3$:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \tag{2.2}$$

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:

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

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 α and β are two Majorana CP violation phases.

If we let a neutrino, ν_α, propagate in time the mass eigenstates will evolve differently (assuming that $m_1 \neq m_2 \neq m_3$), resulting in a new flavor state, ν_β. Massive neutrinos move through time and space as

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

Allowing us to describe the flavor state α at some point in space and time as

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

The oscillation probability that a neutrino produced as flavor ν_α will be detected as flavor ν_β after traveling for a period of time is then given by

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

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

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

and the probability of oscillation is

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

Now we can 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 ($m_\nu << E_\nu$) so we can approximate the momentum 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 we make the reasonable assumption that neutrinos are moving at the speed of light, c, then we can approximate the phase difference, $\phi_2 - \phi_1$, 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 $E_1 = E_2 = E$.

We can now state the oscillation probability of a neutrino, ν_α, being detected as flavor ν_β in the two neutrino mixing case as

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

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

There are several interesting things to note about this probability. We can see that the amplitude of the oscillation probability, $\sin^2(2\theta_{12})$, depends on the mixing angle θ_{12}, while the mass splitting, Δm_{12}^2, the energy of the neutrino, E, and the distance traveled, L determine the frequency of oscillation. The probability is only non-zero when Δm_{12}^2 is non-zero, indicating that if experiments observe 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 tune where they place neutrino detectors based on what features of neutrinos they would like to study. The current best-fit values of the 3-neutrino oscillation parameters are shown in Table 2.2.

Parameter	Best-fit	3σ
Δm^2_{21} [10^{-5} eV^2]	7.37	6.93 - 7.96
$\Delta m^2_{31(23)}$ [10^{-3} eV^2]	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)
δ/π	1.38 (1.31)	2σ: 1.0 - 1.9 (2σ: 0.92 - 1.88)

Table 2.2: The current best-fit values and 3σ allowed ranges of the 3-neutrino oscillation parameters as determined experimentally [1]. The values (values in brackets) correspond to $m_1 < m_2 < m_3$ ($m_3 < m_1 < m_2$).

2.3 Discovery of Neutrino Oscillation

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

$$\nu_e + ^{37}\mathrm{Cl} \rightarrow ^{37}\mathrm{Ar} + \mathrm{e}^- \tag{2.13}$$

in which a neutrino would enter the tank, transform chlorine into argon, which he would then extract and count. In the end Davis and the Homestake experiment calculated a rate of solar neutrinos that was one third of the rate predicted by calculations made by Bahcall using the Standard Model [11]. This became known as the solar neutrino problem and in the following years Bruno Pontecorvo wrote several theoretical papers proposing neutrino oscillation as a solution [12, 13].

Several experiments followed Davis' including SAGE [14], GALLEX [15], and GNO [16, 17], hoping to also calculate the flux of solar neutrinos. All three experiments built detectors based on the reaction $^{71}\mathrm{Ga}(\nu,\mathrm{e}^-)^{71}\mathrm{Ge}$ and all experiments showed a deficit in neutrino flux compared to Standard Model calculations.

More proof for neutrino oscillation came with results from the Super-Kamiokande Experiment [18]. Unlike previous experiments that were only sensitive to electron neutrinos, Super-K detected neutrinos through elastic scattering of electrons which is 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.

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