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Searching for Sterile Neutrinos with the PROSPECT Detector

Karin Gilje* **for the PROSPECT Collaboration**
Illinois Institute of Technology
E-mail: kgilje@iit.edu

PROSPECT, the Precision Reactor Oscillation and Spectrum Experiment, is a phased experiment at the High Flux Isotope Reactor in Oak Ridge National Laboratory. One of the primary physics goals of the experiment is to measure electron antineutrino disappearance from the highly enriched uranium core in order to search for sterile neutrinos. Phase I will consist of a movable 3-ton ^{6}Li loaded liquid scintillator detector with a baseline coverage from 7 to 12 meters from the reactor core. A larger, second detector during Phase II extends the baseline range to 19 meters. This poster describes the predicted sensitivity and discovery potential of the experiment to eV-scale sterile neutrinos using a spectrum-based oscillation analysis.

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*Speaker.

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1. Motivation

Neutrino oscillation is the best indication of physics beyond the standard model. Understanding and describing the oscillation between neutrino flavors can provide important answers to the composition and inner workings of the universe. Nuclear reactor cores, one of many neutrino sources, produce a plethora of electron antineutrinos from the fission process. The fission process has been modeled through several approaches leading to general consensus on the expected shape of the resulting antineutrino spectrum with small ($< 1\%$) disagreements. However, reactor models predict $\sim 6\%$ more neutrinos than are observed by existing flux measurements [1, 2, 3]. There are many possible solutions to this discrepancy, there could be errors in the models based on old measurements or in the nuclear databases used to model the fission processes, or there could be new physics, such as oscillation to a sterile neutrino. The idea of a sterile neutrino, which does not interact via the weak force, has gained preference due to further discrepancies in long baseline experiments such as MiniBooNE and LSND as well as anomalous behavior seen in data from Gallium-based experiments [5]. As a community, there need to be new short-baseline reactor measurements that will address and resolve these issues.

2. PROSPECT Design

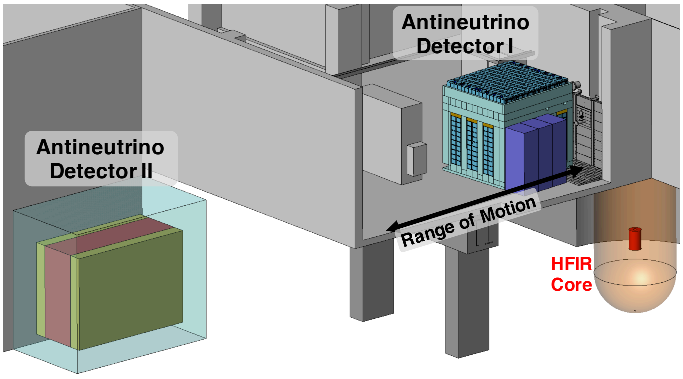

Figure 1: The arrangement of the detectors around the HFIR facility [6].

PROSPECT, the precision reactor oscillation and spectrum experiment, has two primary goals: make a precise measurement of the ^{235}U reactor antineutrino spectrum and perform a search for a $\Delta m^2_{41} = \mathcal{O}(1\text{eV}^2)$ sterile neutrino. PROSPECT will be located near the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). HFIR is a compact, cylindrical research reactor that operates at 85 MW for approximately 47% of the year. Unlike commercial reactors, there is a significant fraction of reactor off time that will be used for in-depth studies of the cosmogenic background.

PROSPECT is a phased experiment, designed to mitigate risk and address experimental situations in a timely manner. The Phase I detector is a 12 x 10 matrix of optically separated segments. Each segment has a 14.6 cm x 14.6 cm cross section and is 120 cm long. At both ends of the segment are 5” photomultiplier tubes (PMT) that allow for improved energy and position reconstruction over a single ended readout. The segments are filled with a commercial liquid scintillator, EJ-309, that is doped with ^{6}Li. There is a total of 2940 kg of target material, of that mass, 1480 kg are in the fiducial volume. Additionally, the detector is movable in order to cover a range of baselines from 7-12 m, as seen in Figure 1. A second farther detector will have the same unit cell as the near detector but will have 4-5 times more target mass and be deployed to increase the baseline up to 20 m from the core, as depicted in Figure 1.

PROSPECT will search for electron antineutrinos through the inverse beta decay (IBD) mechanism, $p+\bar{\nu}_e \to n+e^+$. The positron will immediately annihilate followed shortly by a neutron capture on ^{6}Li. This coincident signature allows strong background rejection leading to a projected signal to background ratio of around 3 to 1. In one year of data taking, the Phase I detector expects to record 115,000 IBD events from the reactor. Extensive Monte Carlo simulations have been performed in order to understand the efficiency (42%), the target energy resolution $(4.5\%/\sqrt(E))$, and the expected detector response, more details can be found in [6].

3. Oscillation Sensitivity

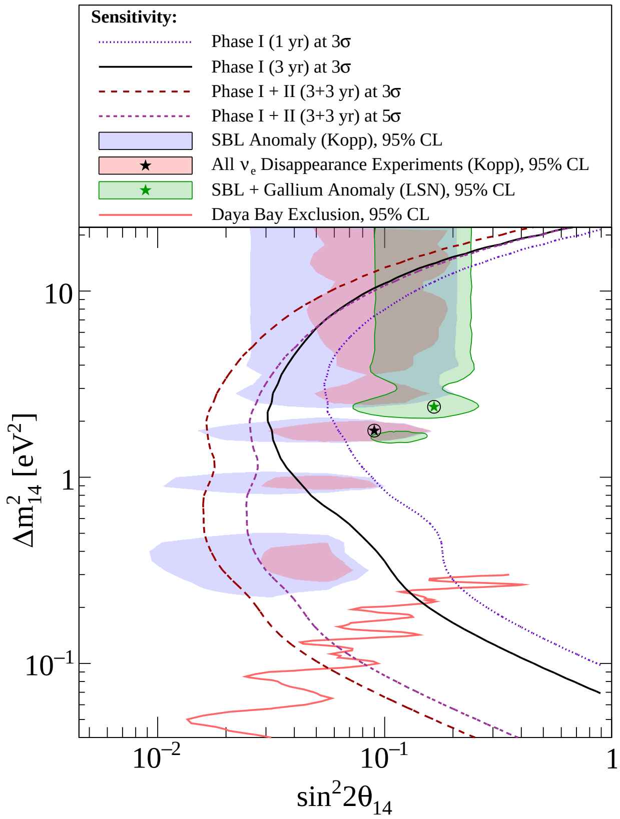

Figure 2: The predicted sensitivity reach into the $\Delta m^2_{14} - \sin^2 2\theta_{14}$ parameter space. Shown are the 3σ sensitivity curves for Phase I at 1 and 3 years of data taking and the 3σ and 5σ curves for Phase II with an additional 3 years of data taking [6]. The Daya Bay contour is from [4]

The sensitivity of the PROSPECT detector was calculated using a minimized χ^2 approach. This χ^2 test was applied between the simulated IBD prompt spectrum (T_{ij}) and the background (B_{ij}) and a toy oscillated spectrum (M_{ij}). The full calculation is

$$\chi^2 = \sum_{i,j} \frac{(M_{ij} - (\alpha + \alpha_e^i + \alpha_r^j)T_{ij} + (1+\alpha_b)B_{ij})^2}{T_{ij} + B_{ij} + \sigma_{b2b}^2 (T_{ij} + B_{ij})^2} + \left(\frac{\alpha}{\sigma}\right)^2 + \sum_j \left(\frac{\alpha_r^j}{\sigma_r}\right)^2 + \sum_i \left(\frac{\alpha_e^i}{\sigma_e}\right)^2 + \left(\frac{\alpha_b}{\sigma_b}\right)^2 \tag{3.1}$$

where the parameters α account for systematic uncertainties in the signal and the background. Specifically,

$$(\sigma, \sigma_b, \sigma_e, \sigma_r, \sigma_{b2b}) = (100\%, 2\%, 10\%, 1\%, 1\%) \tag{3.2}$$

for the reactor flux normalization, the background normalization, the reactor spectrum shape, a position-dependent variation and a bin-to-bin correction respectively. The bin-to-bin correction represents the interdependence between segments. Exclusion contours were determined from the evaluation of a null oscillation model with respect to a 3+1 neutrino model parameterized by (Δm^2_{41}, θ_{14}). Best-fit values for sterile neutrino oscillation from global fits to previous experiments can be excluded above the 3σ level within a single year of data-taking. Within three years of data taking, a majority of the reactor anomaly phase space can be excluded at a high confidence level, as seen in Figure 2. Current work on the sensitivity has focused on the construction of a covariance matrix-based fit. Future functionality will fully include all expected detector systematics and correlations in addition to the dominant reactor-based systematics demonstrated here.

Acknowledgments

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