PROSPECT- A Precision Reactor Oscillation and Spectrum Experiment

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Abstract.
PROSPECT, the Precision Reactor Oscillation and Spectrum Experiment, is an effort to resolve anomalous results observed in previous neutrino physics experiments. The primary physics goals of PROSPECT are to perform a search for short baseline neutrino oscillations ($\Delta m^2 \sim 1$eV$^2$) and to make a high precision measurement of the $^{235}$U reactor antineutrino energy spectrum. PROSPECT will operate close to the Oak Ridge National Laboratory’s High Flux Isotope Reactor, where very little cosmic-ray attenuating overburden is available. To make precision measurements in this difficult environment, PROSPECT has developed a segmented detector design using a $^6$Li-doped liquid scintillator which provides excellent energy resolution and background rejection.

1. Introduction
Over the last several years there has been a resurgence of interest in short baseline (< 20 m) measurements of reactor antineutrinos. This has been motivated by the emergence of two anomalous results based upon reactor antineutrino measurements. First, reexamination of reactor antineutrino flux predictions in preparation for the current generation of $\theta_{13}$ experiments resulted in a significant increase in that flux [1, 2]. Comparison with past flux measurements revealed the “Reactor Antineutrino Anomaly” [3], an average deficit of $\sim 6\%$ in all short-baseline reactor antineutrino measurements. This deficit could be explained by oscillation to one or more sterile neutrinos, with this interpretation being consistent with anomalous results observed in gallium source calibration experiments and the LSND and MiniBoone accelerator experiments (see, e.g., [4]). Alternately, the observed flux deficit could reveal deficiencies in our ability to predict the reactor antineutrino flux due to approximations made in the prediction process or deficiencies in associated nuclear data (see, e.g., [5]). The second anomaly is the recent observation of an excess of events near 5 MeV in high precision and high statistics reactor antineutrino energy spectra measured by Daya Bay, Double Chooz and RENO. This observation also suggests that there are deficiencies in our ability to predict reactor antineutrino emissions and in the data used to make such predictions (see, e.g., [6]).

PROSPECT, the Precision Reactor Oscillation and Spectrum Experiment will address both of these anomalies. By performing a short baseline reactor experiment able to resolve both the antineutrino energy and interaction position with good resolution, PROSPECT will directly test the oscillation interpretation of the reactor flux anomaly in a model independent way. In addition, by performing a measurement of the reactor antineutrino energy spectrum at a reactor...
fueled with highly enriched $^{235}\text{U}$, PROSPECT will provide new experimental data with which to constrain spectrum predictions and to test suggested causes of the spectrum anomaly. To perform these measurements, PROSPECT will have to operate close to a compact core research reactor with little available overburden. Operation of a compact, high efficiency, high resolution antineutrino detection near the surface will demonstrate new capabilities that will expand the reach of reactor monitoring applications.

2. The PROSPECT Experiment

A detailed description of the PROSPECT physics program can be found in [7]. PROSPECT will operate at the High Flux Isotope Reactor (HFIR), located at the Oak Ridge National Laboratory. The HFIR core is comprised of highly enriched $^{235}\text{U}$ and has linear dimensions of $\sim 50$ cm. The location at which the PROSPECT Antineutrino Detector (AD) will be deployed allows a range of antineutrino propagation baselines between $7 - 12$ m to be covered, including movement of the AD itself (Fig. 1). The collaboration has performed extensive characterization of the experimental location, including engineering and background studies [8], which informs the design of the AD and associated shielding.

![Figure 1. The configuration of the PROSPECT experiment. The PROSPECT AD is located close to the compact HFIR core. A range of baselines spanning $7 - 12$ m can be accessed.](image1)

![Figure 2. A cutaway diagram of the PROSPECT AD. A 14 x 11 array of optical segments is surrounded by lead, polyethylene, and water shielding.](image2)

The PROSPECT AD has been designed to provide excellent detection efficiency, energy resolution, position resolution, and background rejection in a space and cost efficient manner. The active volume of the PROSPECT AD will comprise a single acrylic tank containing $\sim 4$ tons of $^6\text{Li}$-doped Liquid Scintillator (LiLS), optically segmented into a 14 x 11 array (154 segments in total). The individual segments have dimensions of 14.6 cm x 14.6 cm x 119 cm and are readout by two 5 inch diameter PMTs placed at either end of the long segment axis. Optical segmentation is implemented using low-mass reflector panels comprised of carbon fiber, specular reflector and a teflon coating, supported by 3D-printed rods. Calibration sources can be introduced through the entire detector volume via the center of the support rods.

PROSPECT has conducted an extensive prototyping and validation program. The optical and mechanical configuration of the AD segments has demonstrated excellent optical collection, response uniformity, and Pulse Shape Discrimination (PSD) performance [7, 9]. Background rejection will be achieved via a combination of shielding and selection cuts. Both of these methods have been designed and validated against prototype data taken in collaboration...
laboratories and at HFIR [7, 8]. With regard to shielding, naturally occurring and reactor produced γ-rays will be suppressed by lead shielding, thermal neutrons will be suppressed by boron-loaded polyethylene shielding, while fast neutrons will be reduced by polyethylene and water shielding. The design of the detector itself is critical to reducing cosmogenic background. Position reconstruction provides the basis for topological selections. We require the prompt and delayed (neutron capture) component of an Inverse Beta Decay (IBD) interaction to be physically proximate. Additionally, events with an energy deposit occurring in the outer layer of segments are rejected (i.e. define an inner fiducial volume), since these are predominantly caused by cosmogenic fast neutrons. The PSD capabilities of the LiS allow rejection of heavy ion recoils caused by cosmogenic fast neutrons, and the positive identification of neutron captures on 6Li. This last capability has two important uses: rejection of the random coincidence of two electromagnetic interactions and rejection of multiple correlated neutrons produced by the interaction of a cosmogenic fast neutron in the detector and surrounding material. A Monte Carlo simulation validated against prototype detector data predicts a signal to background ration of better than 3:1 for the PROSPECT AD operating at HFIR with minimal overburden (Fig. 3).

3. Physics Reach
PROSPECT will provide new experimental data to investigate both the reactor flux and spectrum anomalies. The sensitivity of PROSPECT to short baseline oscillations caused by a sterile neutrino is shown in Fig. 4. Excellent coverage of the phase space suggest by global fits to the various anomalous data sets is achieved. The phase spaced covered at short baselines is complementary to recent exclusions at longer baselines (lower $\Delta m^2$) by Daya Bay [10].

![Figure 3. Predicted antineutrino signal (red) and cosmogenic background (blue) rates for the PROSPECT AD when operated in the location closest to the HFIR core.](image)

![Figure 4. Predicted oscillation sensitivity of PROSPECT after one and three years of data taking.](image)

PROSPECT will greatly improve the precision with which the $^{235}$U reactor antineutrino spectrum is known. Significantly greater statistical precision will be achieved compared to the spectrum measured at ILL [11] (Fig. 5). This measurement will have sufficient precision to distinguish between different predictions of the spectral shape (Fig. 6). The measurement of the effectively pure $^{235}$U reactor antineutrino spectrum emitted by HFIR will provide a unique constraint on spectrum predictions and will be complementary to the high precision measurements now available from experiments conducted at Low Enriched Uranium (LEU).
fueled reactors. Not only will the PROSPECT spectral measurement assist in determining the cause of the observed spectral anomaly, but it could also serve as a benchmark for efforts to use spectral information to better constrain fissile inventories in reactor monitoring applications.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{prob.png}
\caption{PROSPECT will measure $\sim 160,000$ antineutrinos per year, greatly improving upon the statistical precision of past $^{235}\text{U}$ reactor antineutrino energy spectrum measurements.}
\end{figure}

4. Conclusion
PROSPECT will provide timely and important new experimental data for resolving both the reactor flux and reactor spectrum anomalies. A high sensitivity search for the oscillation of reactor antineutrinos to a sterile neutrino at short baselines will stringently test the sterile neutrino interpretation of the Reactor Antineutrino Anomaly in a model independent way. A high precision measurement of the $^{235}\text{U}$ reactor antineutrino spectrum will provide a unique experimental constraint on models seeking to explain the spectral anomaly near 5 MeV. The detector technology developed for the PROSPECT AD could broaden the reach of reactor monitoring applications, particularly the ability to operate with limited overburden. The PROSPECT collaboration is presently constructing the AD and expects to begin data taking in 2017.

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References
[1] Mueller T et al. 2011 Phys. Rev. C\textbf{83} 054615 (Preprint 1101.2663)
[2] Huber P 2011 Phys. Rev. C\textbf{84} 024617 (Preprint 1106.0687)
[3] Mention G et al. 2011 Phys. Rev. D\textbf{83} 073006 (Preprint 1101.2755)
[4] Kopp J, Machado P A N, Maltoni M and Schwetz T 2013 JHEP \textbf{1305} 050 (Preprint 1303.3011)
[5] Hayes A C et al. 2014 Phys. Rev. Lett. \textbf{112} 202501 (Preprint 1309.4146)
[6] Dwyer D A and Langford T J 2015 Phys. Rev. Lett. 114 012502 (Preprint 1407.1281)
[7] Ashenfelter J et al. (PROSPECT) 2016 J. Phys. G43 113001 (Preprint 1512.02202)
[8] Ashenfelter J et al. (PROSPECT) 2016 Nucl. Instrum. Meth. A806 401–419 (Preprint 1506.03547)
[9] Ashenfelter J et al. (PROSPECT) 2015 JINST 10 P11004 (Preprint 1508.06575)
[10] An F P et al. (Daya Bay) 2014 Phys. Rev. Lett. 113 141802 (Preprint 1407.7259)
[11] Kwon H, Boehm F, Hahn A A, Henrikson H E, Vuilleumier J L, Cavaignac J F, Koang D H, Vignon B, Von Feilitzsch F and Mossbauer R L 1981 Phys. Rev. D24 1097–1111