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PROSPECT – A precision reactor oscillation and spectrum experiment

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PROSPECT is a reactor antineutrino experiment whose primary goals are to search for short-baseline neutrino oscillations and perform a precise measurement of the ^{235}U reactor antineutrino energy spectrum. Since March 2018, PROSPECT has operated a 4 ton antineutrino detector less than 10 m from the 85 MW High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory. Operating in this environment with tight space constraints and limited overburden to attenuate cosmic ray backgrounds is a significant technical challenge. The PROSPECT detector design uses efficient optical segmentation and a ^{6}Li-doped liquid scintillator with good light yield and pulse-shape discrimination properties to achieve excellent energy reconstruction and background rejection in a compact, space efficient system. Initial results from PROSPECT have demonstrated the ability to detect 100 s of antineutrino events per day with good signal-to-background in this aboveground location and perform precise measurements of the HFIR antineutrino energy spectrum.

Keywords: Reactor antineutrino detection; neutron detection.

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 ~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., Ref. 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., Ref. 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., Ref. 6).

PROSPECT, the Precision Reactor Oscillation and Spectrum Experiment is designed to 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 directly tests 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}U, PROSPECT provides new experimental data with which to constrain spectrum predictions and to test suggested causes of the spectrum anomaly. To perform these measurements, PROSPECT must operate close to a compact core research reactor with no available overburden. Operation of a compact, high efficiency, high resolution antineutrino detector near the Earth's surface has demonstrated new detection capabilities that can potentially expand the reach of reactor monitoring applications.

2. The PROSPECT Experiment

A detailed description of the PROSPECT physics program can be found in Ref. 7, with a detailed description of the detector itself given in Ref. 8. PROSPECT began operating at the High Flux Isotope Reactor (HFIR), located at the Oak Ridge National Laboratory, in March of 2018. The HFIR core is comprised of highly enriched ^{235}U and has linear dimensions of ~50 cm. The location at which the PROSPECT detector is deployed provides a range of antineutrino propagation baselines between 7–9 m to be covered (Fig. 1). The collaboration has performed extensive characterization of the experimental location, including engineering and background studies,[9] which informs the design of the detector and associated shielding.

The PROSPECT detector has been designed to provide excellent detection efficiency, energy resolution, position resolution, and background rejection in a space- and cost-efficient manner (Fig. 2). The active volume of the PROSPECT AD comprises a single acrylic tank containing ~4 tons of ^{6}Li-doped Liquid Scintillator (LiLS),[10] 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 read out 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.[11] Calibration sources can be introduced throughout the entire detector volume via the center of the support rods.[12]

PROSPECT conducted an extensive prototyping and validation program to arrive at the design of the detector. The optical and mechanical configuration of the segments has demonstrated excellent optical collection, response uniformity, and Pulse Shape

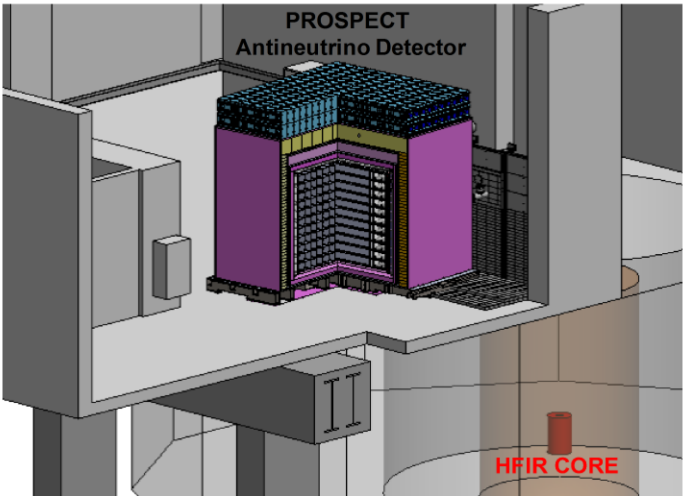

Fig. 1. The configuration of the PROSPECT experiment. The PROSPECT detector is located close to the compact HFIR core.

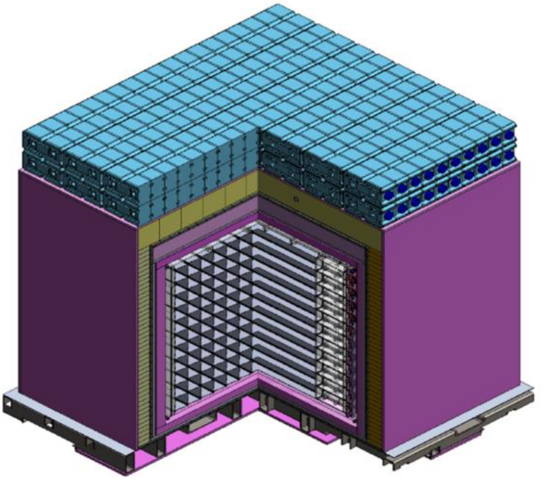

Fig. 2. A cutaway diagram of the PROSPECT detector. A 14 x 11 array of optical segments is surrounded by borated poly (purple), lead (grey), polyethylene (yellow), and water shielding (blue).

Discrimination (PSD) performance.[7,13,14] 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.[7,9] With regard to shielding, naturally occurring and reactor produced gamma-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 LiLS allow rejection of heavy ion recoils caused by cosmogenic fast neutrons and the positive identification of neutron captures on ^{6}Li. 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.

3. Detector Characterization and First Results from PROSPECT

The first results from PROSPECT have recently been published, covering the search for short baseline neutrino oscillation[15] and measurement of the ^{235}U antineutrino energy spectrum.[16] In support of these physics measurements, the PROSPECT detector was extensively characterized through a combination of calibration sources and natural backgrounds. Detector response stability and uniformity are demonstrated via examination of reconstructed physics quantities as a function of time and segment number. Reconstructed energy and energy resolutions are seen to be stable to within ~1% and ~10%, respectively, over all times and segments. Similarly, reconstructed longitudinal positions and uncertainty are stable to within ~5 cm and ~10% respectively.

The energy scale, nonlinearity, and resolution are established via a simultaneous fit to the measured spectra of ^{137}Cs, ^{22}Na, and ^{60}Co sources deployed at segment centers throughout the detector in combination with the high-energy beta spectrum of ^{12}B.[15] The latter is a convenient calibration source that is produced by cosmogenic fast neutrons via the ^{12}C(n,p)^{12}B reaction with a uniform distribution throughout the detector. Despite being highly segmented, the PROSPECT detector achieves an excellent energy resolution of 4.5% at 1 MeV.[16]

To extract antineutrino event rates and spectra, accidental coincidences are subtracted run-by-run during both reactor-on and reactor-off periods with little statistical uncertainty using a pre-prompt window. Correlated cosmogenic backgrounds, dominated by fast neutron interactions, are determined using statistically balanced background data acquired during reactor-off periods. Spectra are scaled by less than 1% to account for variations in atmospheric pressure. Between prompt reconstructed energies of 0.8 MeV

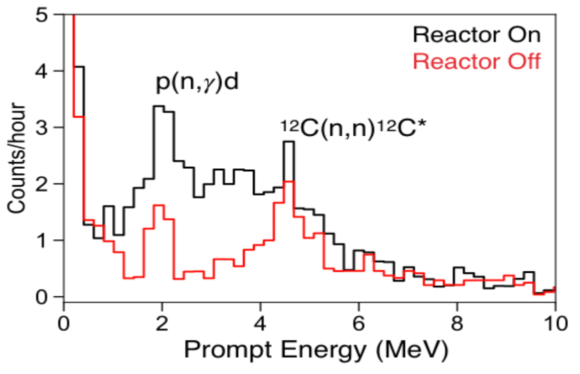

Fig. 3. The prompt energy spectra for the first 24 hours of data with reactor on and off. Both spectra show prominent structure related to cosmogenic backgrounds. The difference is attributed to reactor antineutrino interactions and illustrates the excellent signal to background achieved with minimal overburden.

and 7.2 MeV, the reactor-on data yields 771 detected antineutrino events per day, with a signal-to-background ratio (S:B) of 2.20 and 1.32 for accidental and correlated backgrounds, respectively. This excellent signal to background, the best yet achieved for an antineutrino detector operating with minimal overburden, is illustrated in Fig. 3.

PROSPECT has published two major physics analyses. The first reports results from a search for short baseline neutrino oscillations into a sterile neutrino.[15] Significant phase space is excluded in the Reactor Anomaly region,[3] with the best region being disfavored at >95% confidence (2.3σ). The second reports first precision measurement of the antineutrino spectrum from ^{235}U fission.[16] The result is consistent with the high energy spectrum excess ('bump') seen in measurements at LEU reactors, disfavoring the suggestion that this feature is due to mis-modelling of a single fissile isotope. As described in the reports, both measurements are statistics limited and will improve with further data collection and analysis.

4. Implications of the PROSPECT Aboveground Reactor Antineutrino Detection Demonstration for Monitoring and Safeguards Applications

This first demonstration of a full-scale system operating without cosmic-ray attenuating overburden meets one of the goals set forth by the attendees of the "Workshop on Antineutrino Detection for Safeguards Applications" hosted by the IAEA Novel Technologies Group in 2008.[17] An aboveground detection capability "*will enable a wider set of operational concepts for IAEA and reactor operators, and will likely expand the base of reactors to which this technology can be applied*," since deployments are no longer limited to locations with overburden.

Indeed, the performance of the PROSPECT detector meets or closely approaches the requirements for reactor monitoring capabilities examined by the Applied Antineutrino Physics (AAP) community. The simplest application is monitoring operational status (i.e., is a reactor on or off): PROSPECT can infer the operational status of HFIR to

5 sigma confidence after only two hours of data taking, assuming that the reactor off background rate has been previously measured.[15] The ability to determine reactor operational state (i.e On vs. Off) within time periods useful for monitoring has been found for other research reactor types of nonproliferation interest.[18] While a dedicated sensitivity analysis has not yet been completed, it is also apparent from the collected event statistics, the excellent long-term stability of the detector, and the good signal-to-background ratio,[15] that PROSPECT has the ability to infer reactor power. This is notable, since the detector operates at a high-power research reactor, the sole facility type at which IAEA makes direct power measurements for safeguards.[17] A system like PROSPECT would allow this measurement to be made in a non-intrusive manner with no connection to plant systems. The spectral measurement capability of PROSPECT is more than sufficient for use case studies that have examined the spectrum changes that result from changes to reactor core fuel isotopics.[19] With conceivable increases in background rejection and target mass, a PROSPECT-like detector could meet IAEA timeliness requirements for material diversion.[18]

The next step in technology development for reactor monitoring applications is a high sensitivity, mobile aboveground antineutrino detection capability. This would enable the rapid and non-intrusive deployment of antineutrino systems to essentially any reactor facility. The PROSPECT aboveground demonstration has already motivated a use study based upon this deployment modality.[20] Such a system would also enable spectrum measurements at multiple reactors with different proportions of the main fissile isotopes (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu), providing the means to validate reactor spectrum predictions with common detector systematics and a set of benchmarks for reactor monitoring applications.

5. Conclusion

PROSPECT is providing new experimental data for resolving both the reactor flux and reactor spectrum anomalies. Operating in the challenging environment at a very short distance from a ^{235}U fueled research reactor with essentially no overburden, PROSPECT has conclusively demonstrated the ability to detect reactor antineutrinos. This has been done with good efficiency, signal to background and energy resolution. The detector technology developed for PROSPECT could broaden the reach of reactor monitoring applications, greatly increasing the range of facilities at which antineutrino detectors can be potentially deployed.

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