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Plans For An Aboveground, Redeployment-Ready Reactor Neutrino Detector: PROSPECT-II

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Abstract

In its first run, the PROSPECT experiment reported the world's highest-precision aboveground observations of the neutrino signal from a nuclear reactor. These measurements, collected in 2018 at the HFIR reactor at Oak Ridge, excluded important parameter space in the search for new physics in the neutrino sector. Data from PROSPECT is also sharpening understanding of the neutrino emission from nuclear reactors, with potential value for new safeguards and verification technology. Strengths of the PROSPECT approach are a segmented design and pulse-shape discriminating scintillator, which together enable the best signal-to-background ratio and energy resolution in a surface-deployed reactor neutrino detector. In its second phase, the collaboration is preparing to expand the physics reach and field robustness of this technology. The PROSPECT-II programs aims to definitively resolve the anomalies seen in near-field reactor neutrino experiments with extended data-taking at HFIR and possibly other reactor sites. The upgraded, redeployable detector will also advance the realistic potential of neutrino detectors as a tool for nuclear safeguards and verification.

1 Introduction

Nuclear reactors have been a useful source of neutrinos for particle physics experiments for over 60 years [1]. In the past 40 years, physicists have also discussed the possible use of neutrino detectors in reactor safeguards or nuclear verification [2, 3]. Neutrinos are an appealing signal for these applications because they carry information about reactor power levels and fuel composition out of the containment building, and they cannot be shielded or easily faked. However, the same property that makes neutrinos theoretically attractive—their low interaction cross section—makes them challenging to observe in systems that are reasonably small, portable, and operable on the earth's surface. This document introduces one program, PROSPECT and its planned second stage PROSPECT-II, that is advancing technology along these lines.

2 First Phase of the PROSPECT Program

The Precision Reactor Oscillation and Spectrum experiment, PROSPECT, uses a ton-scale neutrino detector to observe neutrinos from a reactor core. The detector is optimized to observed the inverse beta decay (IBD) interaction of reactor neutrinos with well-controlled backgrounds using minimal cosmic ray shielding. The experiment conducted a first phase of measurements in 2018 at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. From 83 live days of data collected at the highly enriched uranium (HEU)-fueled HFIR reactor, PROSPECT has, among other physics analyses:

- Performed a sensitive search for sterile neutrinos, a hypothesized beyond-Standard Model particle that may explain certain anomalies observed in neutrino experiments [4],
- Measured the energy spectrum of neutrinos produced following the fission of ^{235}U with world-leading precision [4],
- Combined datasets with the STEREO and Daya Bay reactor neutrino experiments to give additional insight into neutrino yield from ^{235}U and a measurement of neutrino yield from ^{239}Pu [5, 6], and
- Provided an empirical basis for a study of one role neutrino detectors could fill in nuclear verification and diplomacy [7].

In meeting these benchmarks, PROSPECT has demonstrated design features which may be relevant for neutrino detectors in reactor safeguards or verification settings that require a portable, meter-scale, aboveground detector deployment:

- A segmented detector design, with the 4-ton active volume divided into 154 optically separate subvolumes, which allows strong rejection of background events that lack the spatial correlation between prompt and delayed signals characteristic of IBD events;
- ^{6}Li-doped, pulse-shape-discriminating (PSD) liquid scintillator, which allows further background rejection through localization of the delayed IBD signal and PSD-based rejection of non-IBD events; and
- Less than 1 meter water equivalent of cosmic ray shielding on top of the active detector.

Together, these features allowed PROSPECT to observe about 50,000 neutrino interactions in its first phase of data-taking, with a signal-to-background ratio of 1.4. A more completed description of the detector design and first phase of data-taking is available in PROSPECT collaboration publications [8, 9, 10, 4].

3 Plans for an Upgrade: PROSPECT-II

The PROSPECT collaboration is now developing an evolutionary upgrade of the PROSPECT detector to deploy for a longer data-taking period at HFIR and possibly other reactor sites. The upgrade will retain successful features of the original PROSPECT design while correcting an issue that allowed scintillator ingress into the photomultiplier tube housings and required a stop in data-taking. The upgraded detector, called PROSPECT-II, will:

- Move the photomultiplier tubes into a volume separate from the scintillator volume, allowing data-taking for a longer period, possibly at multiple reactors;
- Extend the length of the detector segments by 25% and increase the ^{6}Li-doping by 20%, both increasing the signal collection capacity of the detector while retaining its original footprint; and
- Simplify the active detector by reducing materials in contact with the scintillator and using an external calibration system instead of tubes inside the active volume, increasing the detector robustness over time.

The collaboration anticipates deploying PROSPECT-II at HFIR for a two-year run, yielding an order of magnitude more effective statistics than the first run. Redeployment at another reactor site, such as a commercial low-enriched reactor, is a possibility following the HFIR run. More details about the PROSPECT-II upgrade and anticipated physics program appear in a recent collaboration preprint [11].

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