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PROSPECT: a Case Study of Neutrino Physics Research providing Enabling Capabilities for Nuclear Security Applications

Neutrino Frontier Topical Groups: (NF7) Applications
(NF9) Artificial Neutrino Sources

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PROSPECT is a short-baseline reactor antineutrino experiment consisting of a segmented liquid scintillator detector designed to probe the existence of sterile neutrino oscillations and precisely measure antineutrino production by nuclear reactors. To achieve these goals, PROSPECT developed and demonstrated antineutrino detection technologies that provide new capabilities that could enable a broad range of reactor monitoring use cases. This Letter of Interest uses PROSPECT as a case study of how the pursuit of fundamental scientific knowledge can provide new technology to benefit society at large. We encourage ongoing interaction and collaboration between the scientific and application communities and their respective policy-making and funding agencies.

Introduction

Many believe that nuclear power must play a larger role in the world's energy mix if we are to effectively limit carbon emissions. Despite recent headwinds, more nations are building reactors and development of advanced reactor types continues. Novel approaches to nuclear safeguards may be needed if new reactor technologies incompatible with traditional material accountancy approaches gain wide spread adoption. Antineutrino detection could potentially address this need by providing direct and continuous measurements of reactor operation, while also increasing confidence in the intent of new operators and reducing the need for resource-intensive onsite inspections.

Advances in detection technology and understanding of reactors emissions developed for fundamental physics provide the foundational capabilities that allow this application to be considered. The PROSPECT experiment has made important new capability demonstrations that serve as a benchmark for what can currently be achieved and point to new directions to pursue. As described in detail elsewhere [1], there is mutual benefit for the HEP and applications communities from continuing engagement, most notably in technology and capability development and broadening the skill set, experience and professional development opportunities of physicists.

PROSPECT Neutrino Detection Technology

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. 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 (LiLS) with good light yield and pulse-shape discrimination properties [2] to achieve excellent energy reconstruction and background rejection in a compact, space efficient system [3].

Background rejection is achieved via a combination of shielding and selection cuts. 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 backgrounds. Position reconstruction provides the basis for topological selections. The prompt and delayed (neutron capture) component of an Inverse Beta Decay (IBD) interaction are required to be physically proximate. Additionally, events with an energy deposit occurring in the outer layer of segments are rejected, 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.

Demonstration of Enabling Capabilities

PROSPECT has demonstrated the ability to detect 750 antineutrino events per day with a signal-to-background ratio greater than 1 in an aboveground location with almost no overburden [4]. Additionally, PROSPECT has performed a high resolution ^{235}U spectrum measurements in this same adverse background environment [5, 6].

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 [7]. 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 detection performance of PROSPECT demonstrates capabilities underlying reactor monitoring use cases examined by the Applied Antineutrino Physics (AAP) community. The simplest application is monitoring operational status – is a reactor on or off – PROSPECT can infer the operational status of HFIR to 5σ confidence after only two hours of data taking, assuming that the reactor off background rate has been previously measured [4]. Useful operational state sensitivity has been found for other research reactor types of nonproliferation interest [8]. 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 [4], 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 [7]. 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 sufficient for use case studies that have examined the spectrum changes that result from changes to reactor core fuel isotopics [9]. With conceivable increases in background rejection and target mass, a PROSPECT-like detector could meet IAEA timeliness requirements for material diversion [8].

Future Directions for Applications and Overlap with Neutrino Physics Goals

A potential goal for further technology development in the context of 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 detection demonstration has, in part, motivated a use case study based upon this deployment modality [10].

Such a system would also enable spectrum measurements at multiple reactors with different fissile vectors, providing the means to validate reactor spectrum predictions with common detector systematics and a set of benchmarks for reactor monitoring applications. Measurements of this type could contribute to a definitive resolution of the Reactor Antineutrino Anomaly [11] The ability to measure the spectrum of multiple reactors is a development goal for the PROSPECT-II upgrade [12], for the reasons given above.

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