Snowmass2021 - Letter of Interest
Forthcoming Science from the PROSPECT-I Data Set

Neutrino Frontier Topical Groups: (NF02) Sterile neutrinos (NF03) Beyond the Standard Model (NF07) Applications (NF09) Artificial neutrino sources

Contact Information: Nathaniel Bowden (LLNL) [nbowden@llnl.gov]
Karsten Heeger (Yale University) [karsten.heeger@yale.edu]
Pieter Mumm (NIST) [hans.mumm@nist.gov]

M. Andriamirado,[6] A. B. Balantekin,[16] H. R. Band,[17] C. D. Bass,[8] D. E. Bergeron,[10] D. Berish,[13] N. S. Bowden,[7] J. P. Brodsky,[7] C. D. Bryan,[11] R. Carr,[9] T. Classen,[7] A. J. Conant,[4] G. Deichert,[11] M. V. Diwan,[2] M. J. Dolinski,[3] A. Erickson,[4] B. T. Foust,[17] J. K. Gaison,[17] A. Galindo-Uribarri,[12, 14] C. E. Gilbert,[12, 14] C. Grant,[1] B. T. Hackett,[12, 14] S. Hans,[2] A. B. Hansell,[13] K. M. Heeger,[17] D. E. Jaffe,[2] X. Ji,[2] D. C. Jones,[13] O. Kyzylova,[3] C. E. Lane,[3] T. J. Langford,[17] J. LaRosa,[10] B. R. Littlejohn,[6] X. Lu,[12, 14] J. Maricic,[5] M. P. Mendenhall,[7] A. M. Meyer,[5] R. Milincic,[5] I. Mitchell,[5] P. E. Mueller,[12] H. P. Mumm,[10] J. Napolitano,[13] C. Nave,[3] R. Neilson,[3] J. A. Nikkel,[17] D. Norcini,[17] S. Nour,[10] J. L. Palomino,[6] D. A. Pushin,[15] X. Qian,[2] E. Romero-Romero,[12, 14] R. Rosero,[2] P. T. Surukuchi,[17] M. A. Tyra,[10] R. L. Varner,[12] D. Venegas-Vargas,[12, 14] P. B. Weatherly,[3] C. White,[6] J. Wilhelmi,[17] A. Woolverton,[15] M. Yeh,[2] A. Zhang,[2] C. Zhang,[2] and X. Zhang[7]

(The PROSPECT Collaboration)

[1]*Department of Physics, Boston University, Boston, MA, USA*
[2]*Brookhaven National Laboratory, Upton, NY, USA*
[3]*Department of Physics, Drexel University, Philadelphia, PA, USA*
[4]*George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA USA*
[5]*Department of Physics & Astronomy, University of Hawaii, Honolulu, HI, USA*
[6]*Department of Physics, Illinois Institute of Technology, Chicago, IL, USA*
[7]*Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA, USA*
[8]*Department of Physics, Le Moyne College, Syracuse, NY, USA*
[9]*Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA*
[10]*National Institute of Standards and Technology, Gaithersburg, MD, USA*
[11]*High Flux Isotope Reactor, Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[12]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[13]*Department of Physics, Temple University, Philadelphia, PA, USA*
[14]*Department of Physics and Astronomy, University of Tennessee, Knoxville, TN, USA*
[15]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, Canada*
[16]*Department of Physics, University of Wisconsin, Madison, Madison, WI, USA*
[17]*Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA*

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 the antineutrino spectrum of the primary fission isotope ^{235}U. This LOI will describe the physics measurements achieved using data taken during the now-completed phase of the PROSPECT experiment, termed PROSPECT-I. It will also emphasize the additional physics impact that can be expected from modest continued research investment in PROSPECT-I data analysis.

Introduction

PROSPECT is a reactor antineutrino experiment consisting of a segmented liquid scintillator antineutrino detector [1] designed to probe the existence of sterile neutrino oscillations and precisely measure the antineutrino spectrum of the primary fission isotope ^{235}U [2]. Existing data was taken in 2018 and 2019 with a first-generation detector called PROSPECT-I located on the Earth's surface at distances between 6.7 and 9.2 meters from the 85 MW, compact, highly ^{235}U enriched High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. This dataset has already had a substantial impact on the current state of many of the topical groups in the Snowmass 2021 Neutrino Frontier, specifically those related to sterile neutrinos (NF02), artificial neutrino sources (NF09), and applications (NF07). This letter of intent will summarize these impacts and show how further research support for analysis of existing PROSPECT-I data will continue to advance understanding for these and other Neutrino Frontier topical groups.

PROSPECT-I Sterile Oscillation Physics Accomplishments (NF02)

PROSPECT has pursued the physics associated with neutrino mass, one of the five P5 Science Drivers, by probing the existence of neutrino mass states beyond the three associated with the Standard Model neutrinos. In particular, an array of anomalous experimental results may be collectively explained by the existence of one or more new sterile neutrino states with mass splittings of order 1 eV [3]. At nuclear reactors, a transition of electron antineutrinos to undetectable sterile neutrinos can cause deficits in measured inverse beta decay (IBD) detection rates or distortions in measured IBD positron energy spectra [4].

PROSPECT has performed reactor-based oscillation searches with uniquely high sensitivity to large (2-20 eV) mass splittings relative to other reactor-based searches [5–8] due to its use of a high-resolution, segmented short-baseline detector at the spatially compact HFIR core. This small-scale project has yielded high-impact sterile oscillation physics results within five years of release of the P5 report. The first PROSPECT sterile neutrino oscillation search using 33 days of reactor-on data-taking, published in PRL [9], excluded substantial new regions of θ_{14} and mass splitting parameter space. An improved analysis extending sterile neutrino exclusion limits using the full PROSPECT-I dataset is now publicly available [10] and has been submitted for publication in PRD.

Future Sterile Oscillation Physics Goals with PROSPECT-I (NF02)

The PROSPECT and STEREO experiments provide competitive or leading limits on the sterile mixing parameter θ_{14} in the mass splitting regime above a few eV^2 [11], where much of the remaining un-addressed sterile neutrino oscillation parameter space suggested by the reactor flux anomaly lies [12]. PROSPECT plans to improve θ_{14} limits with its existing PROSPECT-I dataset via three avenues:

- Improving signal and reducing background by roughly a factor of two through enhanced IBD selection strategies such as dataset sub-division, cosmic veto development, and machine learning techniques.
- Improving sensitivity at high mass splitting by increasing the granularity of PROSPECT's baseline binning, which will require the use of new statistical techniques [13]
- Enhancing statistical power and L/E coverage by performing joint oscillation analyses with the Daya Bay and STEREO experiments, as previously demonstrated with Bugey-3 and Daya Bay data [14]

We expect these analysis improvements to further expand constraints on θ_{14} in the high mass splitting region. The benefits of joint reactor oscillation analyses to the NF02 topical group are described further in another Snowmass LOI [15].

PROSPECT-I Reactor Spectrum Physics Accomplishments (NF09)

By baseline-integrating the PROSPECT IBD signal and performing detailed calibrations [16], PROSPECT can measure the energy spectrum of neutrinos created following fission of ^{235}U. The combination of pure ^{235}U measurements with knowledge from experiments at low-enriched reactors can yield a more complete picture of the true broad-scale and fine-scale structure of isotopic neutrino spectra and better understanding of the origin of the reactor spectrum anomaly [17–19]. We see these developments as one essential focus of the NF09 topical group, as they would substantially benefit physics outcomes for many topical groups, including NF01 (reactor-based mass hierarchy measurements [20, 21]), NF02 (probing the relationship between reactor spectrum and flux anomalies [22]), NF03 and NF06 (reactor-based CEvNS measurements [23, 24]), and NF07 (relevance to the nuclear data community [25]). The physics impacts of better reactor spectrum knowledge will be described further in another Snowmass LOI [26].

By comparing its first ^{235}U spectrum measurement to the beta-conversion prediction for ^{235}U [27], PROSPECT was able to verify the general accuracy of the model, while providing first indications that ^{235}U is not solely responsible for deviations of Daya Bay's measurement from predictions at high energies. This is by far the most precise absolute measurement of the HEU reactor neutrino spectrum ever performed, and is now published in PRL [28]. Upgrades to the spectrum analysis are complete, and are also reported in Ref. [10]. When considered alongside Daya Bay results [29], this PROSPECT analysis disfavors at greater than 2σ CL the hypothesis that ^{235}U is not at all responsible or entirely responsible for LEU spectrum data-model disagreements.

Future Spectrum Physics Goals with PROSPECT-I (NF09)

Improved signal and background statistics from enhanced PROSPECT-I data analysis will also produce a more precise absolute ^{235}U spectrum measurement. In particular, improved cosmic veto rejection is expected to greatly improve PROSPECT's signal-to-background ratio at high energies, thus substantially enhancing any conclusions PROSPECT-I can draw about the isotopic origin of spectrum discrepancies. Joint neutrino spectrum analyses using the existing PROSPECT-I selection are also currently being performed with the STEREO and Daya Bay collaborations, a short-baseline HEU experiment and a long baseline LEU experiment respectively, to determine the level of compatibility between different HEU and LEU measurements, and to produce new 'data-driven' models of neutrino production by ^{239}Pu and ^{235}U.

Future PROSPECT-I Goals for other Topical Groups (NF07, NF03, NF10)

Beyond its oscillation and spectrum physics goals, future PROSPECT-I analysis will also yield new physics relevant to a variety of Neutrino Frontier topical groups:

- **NF07:** PROSPECT is the first reactor neutrino experiment to achieve a high signal-to-background ratio despite deployment in an overburden-free location. Future PROSPECT-I analysis will demonstrate other capabilities for reactor monitoring applications, such as neutrino directional reconstruction, 3D reactor location, reactor power load-following and sensitivity to plutonium breeding.
- **NF03:** Due to its on-surface location and excellent pulse shape discrimination capabilities, PROSPECT has unique capabilities in direct detection of boosted light dark matter signatures [30]. Analysis efforts are currently underway to using PROSPECT-I data to perform a boosted dark matter search capable of probing regions of parameter space unaddressed by previous direct searches.
- **NF03, NF04, and NF09**: PROSPECT has the capability to perform uniquely precise on-surface cosmogenic neutron, muon, and isotope production measurements. Analyses currently underway using PROSPECT-I data are likely to aid in background modelling for other on-surface experiments, such as NoVA and those in the Fermilab SBN program.

[1] J. Ashenfelter et al. (PROSPECT), Nucl. Instrum. Meth. A **922**, 287 (2019), arXiv:1808.00097 [physics.ins-det].
[2] J. Ashenfelter et al. (PROSPECT), J. Phys. G **43**, 113001 (2016), arXiv:1512.02202 [physics.ins-det].
[3] K. Abazajian et al., (2012), arXiv:1204.5379 [hep-ph].
[4] G. Mention et al., Phys. Rev. D **83**, 073006 (2011).
[5] I. Alekseev et al. (DANSS), Phys. Lett. B **787**, 56 (2018), arXiv:1804.04046 [hep-ex].
[6] Y. Ko et al. (NEOS), Phys. Rev. Lett. **118**, 121802 (2017), arXiv:1610.05134 [hep-ex].
[7] F. An et al. (Daya Bay), Phys. Rev. Lett. **113**, 141802 (2014), arXiv:1407.7259 [hep-ex].
[8] B. Achkar et al., Nucl. Phys. B **434**, 503 (1995).
[9] J. Ashenfelter et al. (PROSPECT), Phys. Rev. Lett. **121**, 251802 (2018), arXiv:1806.02784 [hep-ex].
[10] The PROSPECT Collaboration, (2020), arXiv:2006.11210 [hep-ex].
[11] C. Giunti, Phys. Rev. D **101**, 095025 (2020), arXiv:2004.07577 [hep-ph].
[12] J. M. Berryman and P. Huber, (2020), arXiv:2005.01756 [hep-ph].
[13] X. Ji, W. Gu, X. Qian, H. Wei, and C. Zhang, Nucl. Instrum. Meth. A **961**, 163677 (2020), arXiv:1903.07185 [physics.data-an].
[14] P. Adamson et al. (Daya Bay, MINOS), Phys. Rev. Lett. **117**, 151801 (2016), [Addendum: Phys.Rev.Lett. 117, 209901 (2016)], arXiv:1607.01177 [hep-ex].
[15] B. R. Littlejohn, J. P. Ochoa-Ricoux, B. Roskovec, and P. T. Surukuchi, Joint Experimental Oscillation Analyses in Search of Sterile Neutrinos, Snowmass 2021 Letter of Interest.
[16] J. Ashenfelter et al. (PROSPECT), Nucl. Instrum. Meth. A **944**, 162465 (2019), arXiv:1906.07244 [physics.ins-det].
[17] F. P. An et al. (Daya Bay), Phys. Rev. Lett. **116**, 061801 (2016), arXiv:1508.04233 [hep-ex].
[18] J. Choi et al. (RENO), Phys. Rev. Lett. **116**, 211801 (2016), arXiv:1511.05849 [hep-ex].
[19] Y. Abe et al. (Double Chooz), JHEP **10**, 086, [Erratum: JHEP02,074(2015)].
[20] F. An et al. (JUNO), J. Phys. G **43**, 030401 (2016), arXiv:1507.05613 [physics.ins-det].
[21] F. Capozzi, E. Lisi, and A. Marrone, Phys. Rev. D **92**, 093011 (2015).
[22] A. Hayes, J. Friar, G. Garvey, D. Ibeling, G. Jungman, T. Kawano, and R. Mills, Phys. Rev. D **92**, 033015 (2015).
[23] J. Hakenmüller et al., Eur. Phys. J. C **79**, 699 (2019), arXiv:1903.09269 [physics.ins-det].
[24] J. Billard et al., J. Phys. G **44**, 105101 (2017), arXiv:1612.09035 [physics.ins-det].
[25] Antineutrino spectra and their applications, Nuclear Science NEA/WPEC-25 (2007), `https://www.oecd-nea.org/science/wpec/SG25/`.
[26] A. J. Conant and P. T. Surukuchi, Prediction and Measurement of the Reactor Neutrino Flux and Spectrum, Snowmass 2021 Letter of Interest.
[27] P. Huber, Phys. Rev. C **84**, 024617 (2011).
[28] J. Ashenfelter et al. (PROSPECT), Phys. Rev. Lett. **122**, 251801 (2019), arXiv:1812.10877 [nucl-ex].
[29] F. P. An et al. (Daya Bay), Chin. Phys. C **41**, 013002 (2017), arXiv:1607.05378 [hep-ex].
[30] C. Cappiello and J. F. Beacom, Strong New Limits on Light Dark Matter from Neutrino Experiments, Phys. Rev. **D100**, 103011 (2019), arXiv:1906.11283 [hep-ph].