Physics Opportunities with PROSPECT-II

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EXECUTIVE SUMMARY

Nuclear reactors provide the highest intensity source of pure electron-type neutrinos available on earth. Reactor neutrino experiments have played a central role in developing our current understanding of the three neutrino paradigm and in establishing the current era of precision neutrino physics. Precision measurements of the flavor-pure antineutrino flux from reactors are one way to search for new physics by probing both the physics of neutrino oscillations and the production mechanism of rector antineutrinos. In the years to come reactor neutrino experiments will continue to play an important role in resolving the global neutrino picture. Unique features of reactor neutrinos mean that these experiments can continue to play a leading role in resolving the global neutrino picture.

The PROSPECT experiment has substantially addressed the original 'Reactor Antineutrino Anomaly' by performing a high-resolution spectrum measurement from an enriched compact reactor core and a reactor model-independent sterile neutrino oscillation search based on the unique spectral distortions the existence of eV^2 -scale sterile neutrinos would impart. But as the field has evolved, the current short-baseline (SBL) landscape supports many complex phenomenological interpretations, establishing a need for complementary experimental approaches to resolve the situation.

While the global suite of SBL reactor experiments, including PROSPECT, have probed much of the sterile neutrino parameter space, there remains a large region above 1 eV^2 that remains unaddressed. Recent results from BEST confirm the Gallium Anomaly, increasing its significance to nearly 5σ , with sterile neutrinos providing a possible explanation of this anomaly. Separately, the MicroBooNE exclusion of electron-like signatures causing the Mini-BooNE low-energy excess does not eliminate the possibility of sterile neutrinos as an explanation. In fact, MicroBooNE potentially indicates an oscillation-based deficit in the electron neutrino channel. Focusing specifically on the future use of reactors as a neutrino source for beyond-the-standard-model (BSM) physics and applications, higher-precision spectral measurements still have a role to play.

These recent results have created a confusing landscape which requires new data to disentangle these seemingly contradictory measurements. To directly probe $\overline{\nu}_e$ disappearance from high- Δm^2 sterile neutrinos, the PROSPECT collaboration proposes to build an upgraded and improved detector, PROSPECT-II. It features an evolutionary detector design which can be constructed and deployed within one year and have impactful physics with as little as one calendar year of data.

I. A PRECISION REACTOR OSCILLATION AND SPECTRUM EXPERIMENT

The search for eV²-scale sterile neutrinos is an active area of neutrino physics that is well motivated by theory and by experimental data. In the reactor neutrino sector in the early 2010s, roughly 6% deficit was found in the experiments measuring inverse beta decay (IBD) $\bar{\nu}_e$ interactions from reactors compared to the then recently improved reactor neutrino flux models [1, 2]. This discrepancy, referred to as the Reactor Antineutrino Anomaly (RAA), hinted at the possible existence of a sterile neutrino flavor [3]. Additionally, radiochemical solar neutrino experiments based on gallium found a $\sim 3\sigma$ deficit of detected ν_e interactions from nearby intense radioactive sources, referred to as the Gallium Anomaly (GA) [4]. These two anomalies have prompted an intense global experimental campaign using MeV-scale neutrino sources to test for the existence of sterile neutrinos.

Built in part to provide a definitive search for sterile neutrino oscillations at very short baselines, the PROSPECT experiment was supported by the Intermediate Neutrino Research Program [5] that followed from the 2014 P5 report. PROSPECT provided strong constraints on sterile neutrinos over significant portions of the phase space suggested by the RAA as well as a high-resolution measurement of neutrinos from an HEU core. While successful in supporting many of the collaboration's science goals, the PROSPECT detector suffered from technical problems which cut short its useful life. As described below, the short baseline oscillation landscape continues to evolve, motivating the PROSPECT collaboration to preparing for an evolutionary detector upgrade (PROSPECT-II) that builds from the success of the experiment so far and leverages that existing investment. The PROSPECT-II upgrade, which is described in detail in Ref. [6], resolves technical issues that abbreviated the first run, introduces design features that improve robustness and time-stability, and extends both the depth and the scope of the experiment's physics reach.

II. RECENT RESULTS FURTHER COMPLICATE THE SHORT BASELINE OS-CILLATION LANDSCAPE

A number of experiments including PROSPECT, STEREO, NEOS, DANSS, and Neutrino-4 have probed $\overline{\nu}_e$ oscillations at very short baselines from reactors [7–12]. Each experiment uses model-independent spectral ratio measurements which directly search for energy and baseline dependent spectral distortions that are unique to sterile neutrino oscillations. With the exception of Neutrino-4, the experiments' results have been found to be statistically consistent with the three neutrino model. Neutrino-4 reports evidence for sterile oscillation with 2.9σ significance¹, but is in direct tension with the other reactor experiments and the analysis has drawn criticism [13–15]. Overall, these direct oscillometry experiments have excluded large portions of low- Δm^2 preferred regions for RAA and GA.

As the RAA is based on an observed deficit between the predicted and measured $\overline{\nu}_e$ fluxes at multiple reactor sites, it depends on the accuracy of reactor flux predictions. These predictions are based on neutron-induced fission beta spectra collected by Schreckenbach et al. at the Institut Laue-Langevin (ILL) and converted into neutrino spectra by Huber [1] and Mueller [2] (referred to as the HM model). A recent Kurchatov Institute (KI) measurement of the ratio of the cumulative β -decay spectrum between ²³⁵U and ²³⁹Pu is lower than the ILL/HM value by 5.4% [16]. It was suggested by Kopeikin et al., that this discrepancy is likely due to an overestimation of the absolute normalization of ²³⁵U at ILL. Under this assumption, the re-evaluated flux (KI model) based on the modified normalization produces IBD yields that agree with reactor flux and evolution measurements within 1 σ [17], reducing the significance of the original motivation for the RAA. Though is appears likely that a normalization error contributed to the original RAA, the KI model does not preclude sterile neutrinos from existing in this parameter space as shown in Fig. 1.

New results from SBL reactor experiments, BEST, and MicroBooNE have brought new information and interest in a potential eV-scale sterile neutrino. In contrast to the RAA, the GA requires no reactor flux prediction or knowledge. The initial gallium experiments SAGE and GALLEX were not purpose-built to probe for sterile neutrinos. To directly probe the GA, the Baksan Experiment on Sterile Transitions (BEST) measured the rate of neutrino interactions in a layered gallium detector, with a high intensity ν_e source in the center [18]. To search for oscillations, the rate of production of ⁷¹Ge is measured in inner and outer volumes and compared to expected results. The BEST results show a ~20% deficit in both volumes, strengthening the significance of the GA, but not providing any indication as to whether the deficit is oscillatory in nature.

Neutrino experiments using accelerators have provided intriguing short-baseline anomalies, and remain a highly active avenue for probing sterile oscillations. In the 1990s and 2000s, accelerator neutrino measurements by LSND and MiniBooNE found an excess of ν_e -like and $\overline{\nu}_e$ -like events from predominantly ν_{μ} sources, with the MiniBooNE excess eventually established with 4.8 σ statistical significance [19, 20]. Potential explanations of these results have involved sterile neutrinos, other BSM physical phenomena, or some combination

¹ For consistency, this note uses the published Neutrino-4 results from Ref. [12].

of the two. The corresponding sterile oscillation for this anomaly is in a similar region of the Δm^2 parameter space as the RAA and GA, increasing interest in a sterile neutrino of this scale. Recent results from MicroBooNE using a beam-line and baseline very similar to MiniBooNE show no such excess [21], though their initial sensitivity does not cover the entirety of the MiniBooNE suggested region. Interestingly, MicroBooNE observes a modest deficit in measured ν_e [22], which some interpret as a hint of BSM physics [23].

III. COMPLEMENTARY EXPERIMENTAL APPROACHES TO RESOLVE PO-TENTIAL PHENOMENOLOGICAL EXPLANATIONS



FIG. 1. Left: Comparison of the suggested parameter space from RAA (HM model) [24] and Neutrino-4 [12] to the allowed regions from the RAA (KI model) [24] and excluded parameter regions from global fits of spectral-ratio reactor measurements [25] and KATRIN experiment [26]. Right: Comparison of the suggested parameter space from the gallium anomaly [27] and two ν_e disappearance analyses using MicroBooNE data, one hinting [23] at oscillations and the other [28] excluding a small portion of the parameter space, to the excluded parameter regions from global fits of spectral-ratio reactor measurements [25]. Both cases show regions of interesting parameter space with $\Delta m^2 > 5 \text{ eV}^2$ yet to be explored.

It is worth considering the aforementioned experimental results in a broader phenomenological context to inform future experimental efforts. There is an increasing amount of evidence suggesting that the source of RAA is, at least in part, due to the mismodeling of the reactor $\bar{\nu}_e$ spectra–primarily driven by ²³⁵U. This interpretation is supported by an improved agreement between the measured isotopic IBD yields and the new updated summation model (the Estienne-Fallot or EF model) based on the revised nuclear databases [29] along with the Daya Bay [30, 31] and RENO [32] fuel evolution results and re-evaluated KI-based conversion model. Combined fits of the reactor antineutrino yields and the Daya Bay and RENO evolution data-sets suggest a persistent RAA at ~ 3σ when compared to the ILL/HM model while the anomaly reduces to ~ 1σ when compared to the KI and EF models [24].

When considered in the context of a 3+1 sterile neutrino hypothesis, the EF and KI models have no statistically significant preference for eV-scale oscillations. Though the sterile neutrino explanation of the RAA is diminished with the updated models, the combined reactor rate and evolution data do not preclude the presence of sterile neutrinos in this region, as shown on the left panel of Fig. 1. Viable hybrid models exist that could accommodate incorrect reactor neutrino flux predictions while also allowing oscillations to sterile neutrinos [33]. Rate and flux-evolution measurements alone are not sufficient to unambiguously resolve the reactor anomaly, due in part to reactor power uncertainties and the complex uncertainties in predicting neutrino spectra from fission. Relative spectral measurements, such as those deployed in SBL reactor experiments, are needed for a definitive resolution.

Over the past 5 years SBL reactor experiments performing oscillation searches using relative spectral measurements have collected considerable amount of valuable data. A combined analysis [25] using data from these SBL experiments-including PROSPECT [34], STEREO [8], NEOS [9], DANSS [10], and Neutrino-4 [11]-shows no strong evidence of sterile neutrino oscillations at the eV-scales. The use of relative oscillation searches for this combined fit makes it robust against reactor modeling uncertainties. As shown in Fig. 1, while the combination of these experiments excludes major portions of sterile neutrinos parameter space, a sizeable fraction of the RAA still persists. Moreover, these results are compatible with the gallium results under a 3+1 sterile neutrino model at similar oscillation frequencies. Hence, more data covering $\Delta m^2 > 1 \text{ eV}^2$ are needed to fully explore this parameter space.

The first data release of the MicroBooNE experiment has not shown indications of ν_e appearance from $\nu_{\mu} \rightarrow \nu_e$ oscillations. Nevertheless, the presence of intrinsic ν_e in the beam allows for a ν_e disappearance search with this dataset. One such preliminary analysis [23] performed using the MicroBooNE's data release hints at a 2.2 σ evidence of sterile neutrinos in the similar parameter space as the RAA and the GA with the best-fit point at $(\sin^2(2\theta_{14}) = 0.30 \text{ and } \Delta m_{41}^2 = 1.42 \text{eV}^2)$. A more rigorous fully-consistent 3+1 neutrino oscillation based approach [28] using the same MicroBooNE dataset but including the official MicroBooNE covariance matrix² that accounts for correlated systematic uncertainties sees no hints of oscillations. The results from both these are shown in the right panel of Fig. 1. This analysis excludes portions of parameter space suggested by the MiniBooNE, reactor, and gallium anomalies. The final MicroBooNE dataset, planned to be ~2x the size of the current analyzed dataset, is expected to improve the experiment's coverage but significant portions of the $\sin^2 \theta_{ee}$ parameter space will remain unexplored. The presence of ν_e in the MicroBooNEs ν_{μ} beam produces degenerate effects between ν_e disappearance and νe appearance complicating the interpretations for sterile neutrino oscillation searches. These results highlight the importance of a flavor-pure neutrino source and the need for complementary sterile neutrino searches that can fully address the parameter space suggested by all anomalies shown in Fig. 1.

Looking at the broader picture, MicroBooNE results so far don't resolve the decadeslong MiniBooNE [22] and LSND [19, 35] anomalous results. Moreover, the reconciliation of LSND, MiniBooNE, and MicroBooNE results demand invocation of a combination of multiple non-vanilla BSM models. The picture gets even more complicated when datasets from reactor and gallium experiments are included. A key point to note is that while the gallium experiments were so far only able to probe the deficit and can't disambiguate between effects arising from oscillations or an unknown production effect, relative reactor searches have the powerful capability to directly search for the propagation effect induced by neutrino oscillations. Ultimately, the consolidation of these paradoxical results necessitates the need for multiple complementary probes to disentangle multiple competing BSM effects.

Despite significant experimental, theoretical, and phenomenological progress in the reactor, gallium, and long baseline sectors, a consistent description of the neutrino picture hasn't emerged yet. The combined picture of all the anomalous results cannot be fully explained using a 3+1 sterile neutrino picture highlighting the need for multiple complementary efforts to comprehensively probe the anomalies.

² Note that neither of these analyses are performed by the MicroBooNE collaboration and the outcomes from the official analysis may vary slightly.



FIG. 2. Sensitivity contours from one year (black, solid) and two years (pink, solid) of PROSPECT-II [6] data-taking compared to: Left: Already excluded parameter space from the relative reactor spectral experiments (gray, dashed), and the allowed region (blue, solid) from RAA (KI model), Right: Suggested parameter space from GA and Neutrino-4 experiment (pink) and the CP violation disambiguity limit (red, dashed). PROSPECT-II can significantly increase the global sensitivity in the 1-10 eV² range. Additionally, PROSPECT-II in conjunction with the projected sensitivity (dashed, teal) from KATRIN [26] will be able to exclude all of the GA suggested parameter space and clear up the CP violation disambiguity.

IV. PROSPECT-II: UNIQUE INPUTS FOR THE RESOLUTION OF SHORT BASELINE ANOMALIES

In light of these recent developments, the physics opportunities for PROSPECT-II become even more tantalizing. In 2021, the PROSPECT collaboration published a detailed summary of the physics opportunities with an upgraded detector which can be rapidly deployed [6]. As detailed above, both MicroBooNE and the gallium experiments point to preferred parameter space in the few- eV^2 region, with oscillation amplitudes just beyond what has been probed by the current generation of SBL reactor experiments.

Reactor experiments are highly complementary to accelerator- and source-based measurements and feature a flavor-pure, high-intensity source of $\overline{\nu}_e$. While there have been questions about the uncertainties in absolute flux predictions, segmented detectors at short baselines are able to directly search for energy-dependent oscillation-induced spectral distortions that are the 'smoking-gun' of sterile neutrinos. This model-independent technique is crucial to positively identify neutrino oscillations as opposed to an ambiguous flux-deficit that could be caused by a mismatch between data and theoretical predictions. The energies (~few MeV) and baseline (7-9 m) available to PROSPECT-II at HFIR are uniquely suited to searching for oscillations in the 1–10 eV² region. The projected PROSPECT-II sensitivity will surpass the current global analysis' precision at all Δm^2 above ~2 eV² with as much as 2 to 4 times improvement for mass-splittings in the 5–10 eV² region.

The Neutrino-4 collaboration reports a $\sim 3\sigma$ oscillation-like signal with a best-fit point of $\sim 7.3 \text{ eV}^2$ and an amplitude of $\sin^2 2\theta = 0.36$. The allowed region is shown in Fig. 2. This best-fit point is in tension with results from PROSPECT and STEREO. By probing this broad-region of parameter space, PROSPECT-II can play a valuable role in the resolution of the aforementioned confusing experimental and theoretical landscape.

While testing the presence of an additional sterile state is an important BSM study in its own right, it is also crucial for the future studies of Standard Model neutrino parameters. Results from upcoming long baseline (LBL) experiments designed to measure CP-violation remain ambiguous [36–39] if sterile neutrinos are not fully excluded for mixing angles $\sin^2 2\theta \gtrsim 0.03$ [40]. Thus a combination of PROSPECT-II, tritium beta endpoint measurements, and medium baseline neutrino experiments together will play a complementary role in the interpretation of the future LBL results.

V. PROSPECT-II: BENCHMARK MEASUREMENTS FOR PRECISE UNDER-STANDING OF REACTOR $\overline{\nu}_e$ EMISSION

There are additional scientific goals that the PROSPECT-II upgrade can achieve. These primarily relate to greatly improving our understating of reactors as an antineutrino source which would benefit neutrino physics, BSM studies, and safeguards applications using neutrinos.

Comparisons of experimental and predicted $\overline{\nu}_e$ energy spectra measured at LEU-fueled reactors show sizable disagreements, most prominently in the 4-6 MeV energy range. PROSPECT-II will help to address this situation by further improving the precision of the world-leading PROSPECT measurement of the ²³⁵U $\overline{\nu}_e$ energy spectrum. As described in Ref. [6], PROSPECT-II will produce a spectrum measurement that approaches or exceeds the precision of current prediction approaches, providing a stringent test of the underlying models and nuclear data. Furthermore, a joint analysis of spectrum measurements from Daya Bay and PROSPECT-II would produce purely data-driven reactor $\overline{\nu}_e$ spectrum models for future particle physics measurements and potential applications. Benchmark spectra have been identified as a high-priority "nuclear data" need during a recent community workshop [41].

PROSPECT-II will also perform a precise measurement of the $\bar{\nu}_e$ flux produced in ²³⁵U fission. By performing a modern ²³⁵U $\bar{\nu}_e$ flux measurement, PROSPECT-II can increase the reliability of the global flux picture, similarly benefiting the particle physics and nuclear science communities. A flux precision of 2.5% is anticipated, with the dominant systematic being knowledge of the HFIR power (~2%). When combined with flux measurements at LEU fueled reactors that have a more complex fuel mix, the pure ²³⁵U $\bar{\nu}_e$ flux measurement performed by PROSPECT-II would improve the precision of IBD yields from all major fissioning isotopes [6].

VI. PROSPECT-II: AN EVOLUTIONARY DETECTOR UPGRADE WITH PHYSICS RESULTS WITHIN 2 YEARS

The original PROSPECT detector initially met all design requirements, as laid out in Ref. [42]. Unprecedented background rejection, provided by detector segmentation and particle identification via Pulse Shape Discrimination using a ⁶Li-doped liquid scintillator [43, 44], allowed precision reactor antineutrino measurements to be conducted near the earth's surface with very little overburden. Excellent energy resolution, precision energy calibration and reconstruction, and event position reconstruction [45] in a compact detector enabled model-independent short baseline oscillation searches and modern antineutrino energy spectrum measurements from ²³⁵U fission [7, 34, 46].

As in the original PROSPECT design, the PROSPECT-II detector will contain a segmented ⁶Li-doped liquid scintillator volume optimized for inverse beta decay detection with minimal cosmic-ray shielding. The PROSPECT-II detector design addresses technical issues encountered during the initial data taking period that caused a fraction of the detector PMTs to become inoperable. The principal design change moves the PMTs outside the liquid scintillator volume, thereby eliminating the possibility of liquid scintillator affecting voltage divider operation. Additionally, this change reduces the range of materials in contact with the liquid scintillator, providing an improved environment for long-term stability and operation. Completing the upgrade involves rebuilding the inner scintillator containment vessel, the production of new liquid scintillator, and a revamped calibration deployment scheme. Components outside this inner region, including an outer liquid containment vessel, an extensive shielding package and data acquisition electronics are largely unchanged. These evolutionary changes require modification to a minority of subsystems and are expected to maintain the demonstrated performance achieved during initial PROSPECT operation.

Based on the demonstrated construction timeline of PROSPECT, the PROSPECT-II detector can be built and deployed within one calendar year of project start. This ability to leverage existing components and expertise makes it possible for PROSPECT-II to rapidly begin collecting the largest ever data set from an isotopically pure source of ²³⁵Ufissions at the High Flux Isotope Reactor. Impactful physics results can then be produced with as little as one calendar year of data, with full sensitivity being reached after 14 reactor cycles (Fig. 2). With a timely start, this can be comfortably achieved prior to a long reactor outage planned for 2028 [47].

VII. SUMMARY

Short-baseline reactor experiments have been very successful in probing low-mass ($<1eV^2$) sterile neutrinos, though sensitivity to the high- Δm^2 region remains limited. MicroBooNE and BEST have generated renewed excitement about the possibility of high- Δm^2 sterile neutrinos. Efforts to interpret these results have demonstrated the need for new and enhanced data that can probe this region. The KATRIN experiment is beginning to probe the > 10 eV² region and the θ_{13} reactor experiments have effectively covered the low- Δm^2 region, leaving an opportunity for short-baseline reactor-based experiments to probe for 1– 10 eV² mass-splittings. We highlight the unique contributions that the recently proposed PROSPECT-II physics program can make to this exciting landscape. By rapidly deploying a robust detector, it is possible to explore this region for new physics in a two-year timeline.

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