Opportunities for the Precision Study of Reactor Antineutrinos at Very Short Baselines at US Research Reactors

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Antineutrinos from nuclear reactors have played an important role throughout the history of neutrino physics. From the observation of the electron antineutrino [1] to the discovery of electron antineutrino disappearance in KamLAND [2] and the recent measurements of the neutrino mixing angle θ_{13} [3–5], reactor antineutrinos have been central to our current understanding of neutrinos and neutrino properties. Reactor antineutrinos are also used to search for neutrino magnetic moment and coherent scattering. In recent years, the flux of antineutrinos from nuclear reactors has been used to monitor the operation of nuclear reactors [6] and efforts are underway to study the burnup and isotopic composition of nuclear fuel by measuring the time-dependence of the reactor antineutrino flux and spectra. Since their discovery fifty years ago, neutrinos have become a probe of fundamental physics, astrophysics, and applied nuclear science. Neutrinos from nuclear decays are the only flavor-pure source of neutrinos and offer unique possibilities in the study of neutrino properties and flavor transformation.

Anomalous results from a variety of neutrino experiments, astrophysical observations, and cosmology can be interpreted as evidence for the existence of sterile neutrinos – additional neutrino mass states beyond the three active species in the Standard Model (SM). Most recently, a re-analysis of short-baseline reactor neutrino experiments has revealed a discrepancy between observations and the predicted antineutrino flux. While the shape and uncertainties obtained in this recent work are comparable to previous predictions the normalization is shifted upwards by about 3.5% [7]. When combined with experimental data at baselines between 10-100 m these recent calculations suggest a 6% difference between the measured and predicted reactor antineutrino flux.

This reactor anomaly can be interpreted as a sign of new physics or could be due to an unknown issue with the reactor antineutrino flux predictions. It has been suggested that such deficit maybe the signature of additional sterile neutrino states with mass splittings of the order of $\sim 1\text{eV}^2$ and oscillation lengths of $\mathcal{O}(3\,\text{m})$ [8]. Current km-scale reactor experiments, while highly precise, cannot probe such short oscillation lengths. At these baselines the oscillation effect from potential sterile states averages to yield an effective rate deficit. Moreover, these measurements will eventually be limited by the understanding of the contribution of multiple reactor cores, the presence of oscillation effects, and by the inability to take background data without the presence of any reactor $\overline{\nu}_e$. *A new experiment at very short baselines in a controlled research environment is needed to fully disentangle the possible contributions from reactor flux and spectrum prediction uncertainties from sterile neutrino oscillation effects, or other signs of new physics.*

One experimental approach [9–11] is to measure the reactor antineutrino flux from compact research reactors at distances comparable to the expected oscillation length of $\mathcal{O}(3\,\text{m})$ of sterile neutrinos. A measurement of the $\overline{\nu}_e$ rate and energy spectrum as a function of distance can be used to search for the signature of sterile neutrinos. At these baselines the finite dimensions of the reactor core, the spread in the position resolution of events inside the detector, and the limited energy resolution of compact detectors have to be taken into consideration. Compact reactor cores with dimensions of <1 m and segmented detectors are well suited to minimize the neutrino path length effects. Research reactors operating over several fuel cycles per year offer a unique environment to study the time-variation of reactor $\overline{\nu}_e$ spectra as a function of the core's isotopic composition and to compare with state-of-the art reactor simulations and $\overline{\nu}_e$ predictions. The use of highly-enriched uranium (HEU) fuel in US research reactors offers a unique isotopic core composition that may help probe our understanding of reactor $\overline{\nu}_e$ calculations. The duty cycle of research reactors allows for extensive background measurements and the fuel handling at these facilities may enable dedicated studies of spent nuclear fuel that have not been possible at commercial power plants.

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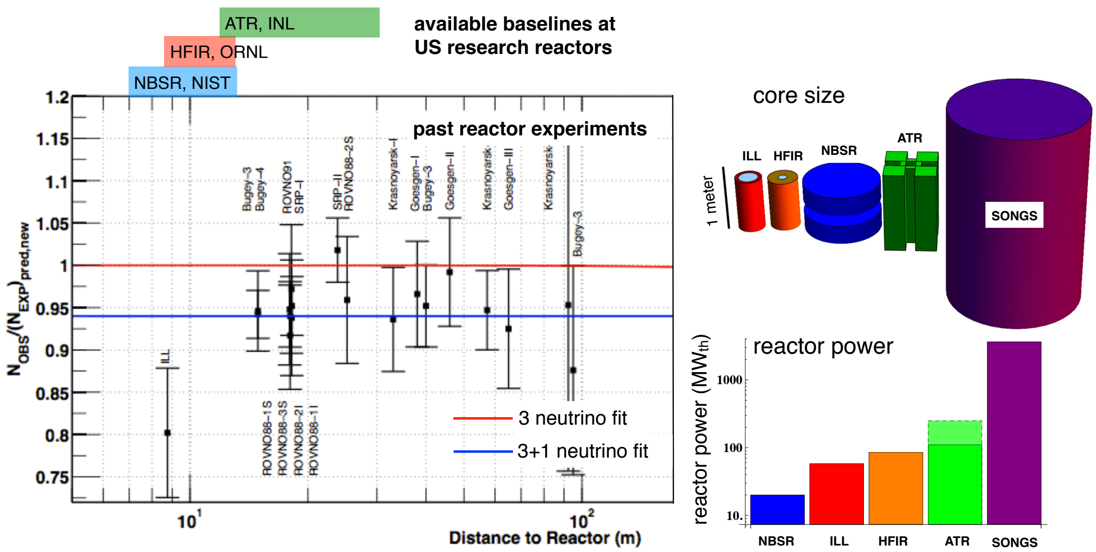

FIG. 1: Left: Reactor $\overline{\nu}_e$ flux measurements in reactor experiments up to ∼100 m baseline. Existing measurements are shown in black. The blue, red, and green bands indicate the distances at which new experiments at NBSR, HFIR, or ATR are feasible. Figure adapted from [7]. Right: Comparison of the size and power of several reactors cores. For ATR, both the typical operating power and the higher, licensed power are shown. Figures from M. Tobin.

The National Institute of Standards and Technology (NIST) [12] and Oak Ridge National Laboratory (ORNL) [13] operate powerful, highly compact research reactors for neutron research. Idaho National Laboratory (INL) [14] is host to the Advanced Test Reactor (ATR). All laboratories provide user support for external scientific users. The National Bureau of Standard Reactor (NBSR) at NIST, the High Flux Isotope Reactor (HFIR) at ORNL, and ATR at INL have identified potential sites for a compact $\overline{\nu}_e$ detector at distances between 4-13 m, 7-13 m, and 12-30 m from the reactor cores, respectively [18]. NBSR offers the opportunity for a new $\overline{\nu}_e$ flux and spectra measurement at the closest distance yet wile HFIR and ATR offer superb power for their compact core size. The higher power and $\overline{\nu}_e$ flux of ATR and HFIR is balanced by the slightly closer distance of NIST. Assuming a 1×1×3 m (height×width×length) detector with 30% efficiency at either one of these locations, a measurement with 1 year $\overline{\nu}_e$ lifetime would cover the majority of the currently preferred parameter space of the reactor anomaly at 3σ C.L. Figure 1 summarizes the accessible baselines and illustrates the comparison of several reactor cores in terms of dimension, geometry, and thermal power. Also included is the commercial power plant SONGS with a deployment site at 24m baseline [19]. While SONGS' larger core dimension limits sensitivity to larger neutrino mass splittings, the high antineutrino flux and available overburden make it useful for detector commissioning and characterization. In addition, measurement of the SONGS antineutrino spectrum may help further constrain flux predictions uncertainties, especially when combined with a similar measurement of an HEU core. Figure 2 shows the 3σ discovery potential for the different sites and illustrates the effect of different signal to background conditions. *A precision $\overline{\nu}_e$ experiment at very short baselines provides significant discovery potential to the currently favored sterile neutrino oscillation parameters.*

A precision reactor $\overline{\nu}_e$ experiment at very short baselines will require a novel detector and shielding design. Reactor $\overline{\nu}_e$ experiments typically utilize the inverse beta-decay reaction $\overline{\nu}_e + p \rightarrow e^+ + n$ yielding a prompt signal followed by a neutron capture tens of microseconds later. The delayed coincidence allows for a significant reduction in accidental backgrounds from natural radioactivity and gammas following neutron capture. The major experimental challenge is expected to come from the lack of overburden and the need to operate the detectors close to the reactor core. At a few meters from the reactor core, the available overburden for the reduction of cosmogenic backgrounds is minimal. Fast neutron backgrounds from cosmic rays, the reactor, and adjacent experiments will contribute significantly to the ambient backgrounds near the reactor. In spite of these challenges, recent developments of antineutrino detectors for non-proliferation and nuclear verification efforts have demonstrated the feasibility of $\overline{\nu}_e$ detection in such a situation. The development of a precision reactor $\overline{\nu}_e$ detector operating in this environment will offer a range of R&D opportunities with applications in gamma and neutron shielding, neutron detection, and reactor monitoring.

A key element in the $\overline{\nu}_e$ detection is the proton-rich scintillator target. Metal-loaded scintillators based have been the state of the art in reactor $\overline{\nu}_e$ experiments [20]. Recent developments of water-based scintillators [21] offer attractive alternatives with different systematics and characteristics. Novel Li-doped scintillators [22] may be used to improve on neutron detection efficiency and minimize the gamma leakage. Choice and composition of the scintillator is important for the timing of the delayed coincidence signal, the accidental background suppression, the energy response, and

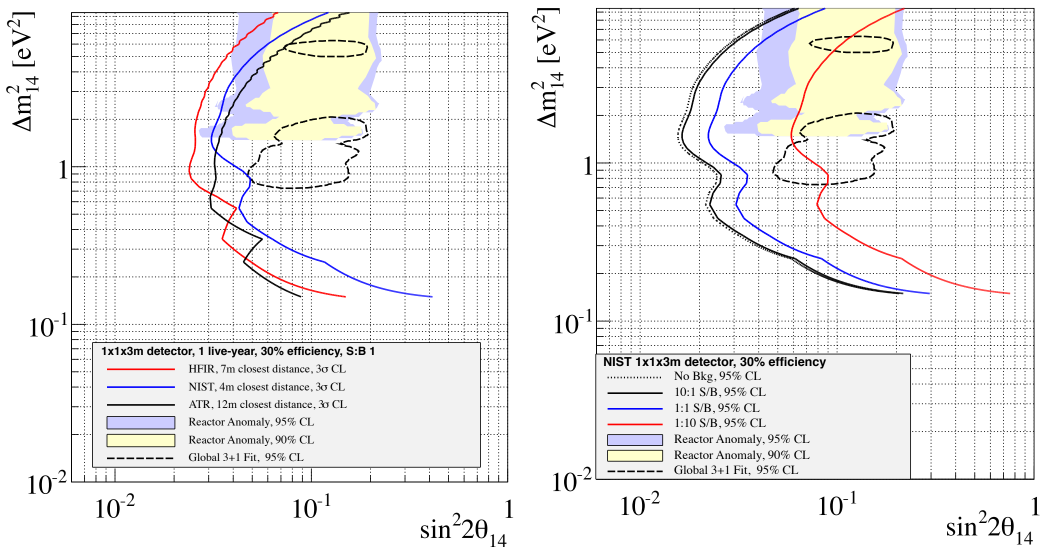

FIG. 2: Left: 3σ discovery potential compared with the favored parameter space of the reactor anomaly and the global best fit [8]. Right: Exclusion limits at 95% C.L. for different signal to background ratios, S/B. Background suppression will be one of the major design and R&D challenges for an $\overline{\nu}_e$ detector under minimal overburden.

possible veto efficiency against muons. The detector design is critical for identifying the baseline-dependent variation of a possible oscillation signal. A modular, segmented detector, for example, may help with the position resolution of events and at the same time provide a unique opportunity for studies and testing of different scintillators.

In summary, the reactor facilities operated by US national laboratories offer a unique opportunity for the deployment of an advanced, compact $\overline{\nu}_e$ detector with the potential to resolve one of the outstanding anomalies in neutrino physics. The development of a definitive reactor $\overline{\nu}_e$ experiment at very short baselines has broad impact with applications in many areas of nuclear science ranging from scintillator development, neutron detection, and radiation shielding to our understanding of $\overline{\nu}_e$ emission from nuclear reactors and safeguard applications.

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