Yale High Energy Physics Research: Precision Studies of Reactor Antineutrinos

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1 Precision Studies of Reactor Antineutrinos

1.1 Project Summary

This reports presents experimental research at the intensity frontier of particle physics with particular focus on the study of reactor antineutrinos and the precision measurement of neutrino oscillations. The experimental neutrino physics group of Professor Heeger and Senior Scientist Band at Yale University has had leading responsibilities in the construction and operation of the Daya Bay Reactor Antineutrino Experiment and made critical contributions to the discovery of non-zeroθ_{13}. Heeger and Band led the Daya Bay detector management team and are now overseeing the operations of the antineutrino detectors. Postdoctoral researchers and students in this group have made leading contributions to the Daya Bay analysis including the prediction of the reactor antineutrino flux and spectrum, the analysis of the oscillation signal, and the precision determination of the target mass yielding unprecedented precision in the relative detector uncertainty. Heeger's group is now leading an R&D effort towards a short-baseline oscillation experiment, called PROSPECT, at a US research reactor and the development of antineutrino detectors with advanced background discrimination.

2 Group Overview

The experimental neutrino group supported by this award consists of Professor Karsten Heeger, Director of the Wright Laboratory at Yale University, Senior Scientist Henry Band, postdoctoral researcher Tom Langford, and two graduate students. During the period of this award Christine Lewis and Michael McFarlane completed their dissertation at the University of Wisconsin. A new graduate student Danielle Norcini from Yale University has joined the group. Heeger's group has provided regularly research opportunities for undergraduates throughout the semester.

The primary focus of the group's research activities is on the precision study of reactor antineutrinos. Over the period of this award the group's main activities involved the operation and analysis of the Daya Bay experiment [1] and preparation for a new short-baseline reactor neutrino experiment called PROSPECT [2].

For over a decade Heeger's group has led investigations in low-energy neutrino physics and the study of reactor neutrinos. The group has made critical hardware and analysis contributions to the KamLAND [3, 4] and Daya Bay reactor neutrino experiments, and Heeger is now leading a US collaboration towards the development of a novel reactor experiment at very short baselines, called PROSPECT. In summer 2013 Heeger and his research program moved from the University of Wisconsin to Yale University. The work described here was performed at Yale University. As a member of the Yale HEP group and Director of the Wright Laboratory, Heeger is leveraging new and remodeled facilities at Yale University to build a synergistic neutrino program integrating Yale's high-energy and low-energy neutrino activities for the development of next-generation neutrino detectors.

3 Research Accomplishments

3.1 Daya Bay

Reactor neutrino experiments have played a key role in the history of neutrino physics [5]. The Daya Bay reactor neutrino experiment was designed and built between 2007-2012 for the precision measurement of the neutrino mixing angle θ_{13}. Utilizing a relative measurement of the flux and spectrum of reactor antineutrinos at distances near and far from a reactor with baselines up to 2 km it provided the discovery of a non-zero value for the neutrino mixing angle θ_{13} [7] and made the most precise measurement of θ_{13} to date [8]. Current measurements of Daya Bay are still statistics limited, and data taking continues to improve on the precision of θ_{13} and Δm^2_{ee}. Daya Bay's measurement of θ_{13} will be the reference for years to come. The continued measurement and improvements in the determination of θ_{13} are important for precision oscillation studies with a future long-baseline neutrino experiment, improve the ability to determine CP violation and help maximize the physics potential of future experiments [6]. Figure 1 illustrates the current and future precision of the Daya Bay measurement. Another $\sim$2 years of data taking followed by analysis are needed to reach the systematic limit. Figure 1 illustrates the importance of a precision measurement of θ_{13} on future experiments. With the high-statistics data collected by the detectors near the nuclear power plant Daya Bay will provide the most precise measurement of the reactor antineutrino spectrum of all currently operating experiments and help test the validity of reactor flux calculations.

Heeger and his group have had overall responsibility for the design, construction, deployment, and installation of the eight antineutrino detectors and are now maintaining the operations of the completed antineutrino detectors. Specific hardware contributions to the detector system included the design and fabrication of the acrylic target vessels [9, 10], the construction of a precision liquid filling and mass measurement system [11], the detector monitoring instrumentation [11], and general installation planning and oversight [12]. The precision measurement of Daya Bay's target mass by Heeger's group reduced the dominant systematic error of the experiment on the target protons by a factor of 15 and made it negligible. An early physics run of the experiment with a partial configuration of six antineutrino detectors detectors was suggested by Senior Scientist Band and was made possible installation planning and sensitivity studies provided by the science and engineering team led by Band and Heeger. This early physics run led to the discovery and first measurement of non-zero θ_{13} in March 2012 [7, 13].

Progress& Results
During the period of this award Heeger and his group have continued their role in the operation, data taking and analysis of the Daya Bay experiment and served in several leadership positions of the collaboration. Heeger is an elected member of the Daya Bay Executive Board and was re-elected in February 2014 for another 2-year term. Heeger is a co-convener of the Daya Bay reactor flux physics working group and assists in coordinating the analysis of the measurement of the reactor spectrum at Daya Bay. Two results of this work, the measurement of the absolute reactor flux, and the measurement of the absolute spectrum were released in spring and summer 2014 respectively. As a member of the Daya Bay Executive Board, Heeger has contributed to defining the run plan for Daya Bay and evaluating the physics potential of Daya Bay up to FY17 and beyond. The precision measurements of reactor antineutrino oscillation parameters as well as a study of the reactor spectrum and its evolution are Daya Bay's key goals for the

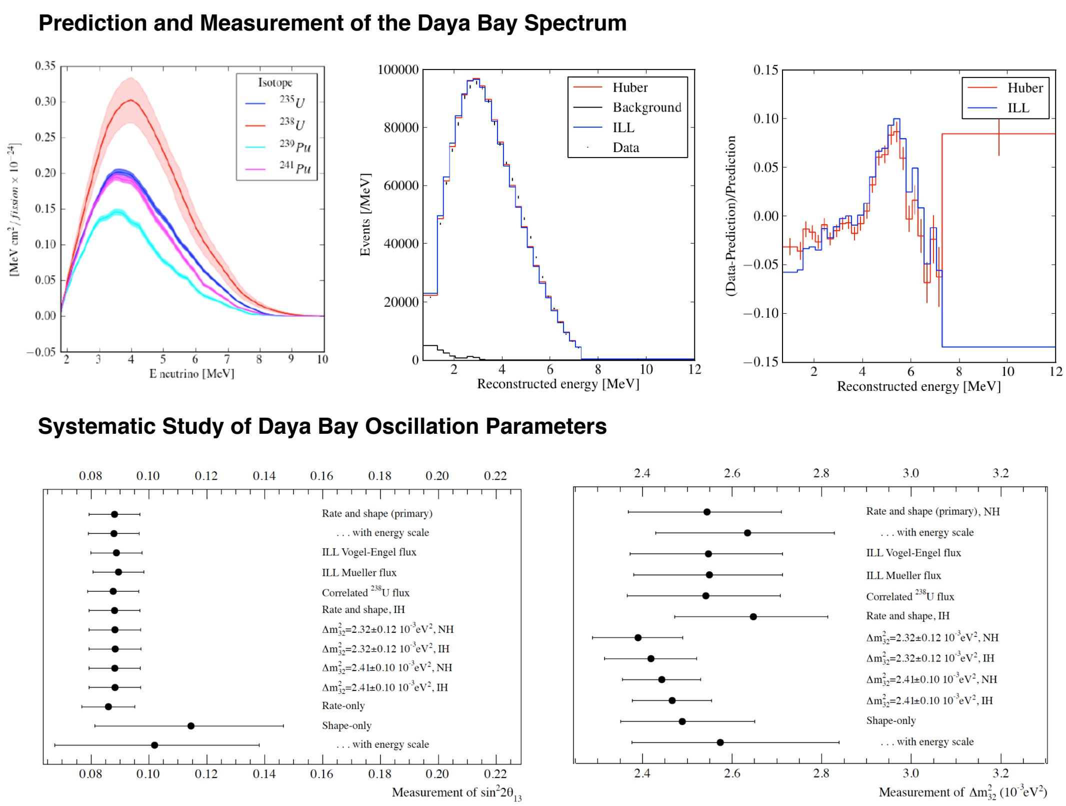

Figure 1: Top left: Prediction of the absolute Daya Bay reactor antineutrino spectrum based on a model of the nuclear isotopes. Top middle and right: Measured Daya Bay reactor spectrum compared to expectations. This work is based on the thesis work of graduate student Christine Lewis. Her work served as the basis for results released by the Daya Bay collaboration in summer 2014 and contributes to an upcoming publication on the absolute spectrum measurement. Bottom: Systematic study of the sensitivity of the Daya Bay oscillation parameters from a rate-only, shape-only and rate+shape analysis of the Daya Bay spectrum. This work is from the dissertation of graduate student Michael McFarlane. Both Lewis and McFarlane graduated in Spring 2014 during the period of this award. Their work has been used in the preparation of Daya Bay publications.

next few years.

Senior research scientist Henry Band served as the Level-3 manager for the Antineutrino Detector assembly and coordinated the installation and scheduling of the experiment on-site. He now convenes regular operations meetings of the collaboration to ensure high-quality data taking, oversees the maintenance of the antineutrino detectors. Data taking, detector maintenance and operations are expected to continue throughout FY15 followed by final data analysis activities in FY16-17. Senior scientist Band continues to oversee the antineutrino detector operation activities, regularly evaluates the health of the detectors, and organizes repair and maintenance activities as needed. Band provides the continuity and long-term oversight needed for stable data taking through the completion of the experiment. Regular activities include monitoring the liquid levels, cover gas, temperature, and the precision determination of detector target mass. In addition, Band and others from Heeger's group will provide assistance in data quality shifts and detector calibrations. Band has been appointed as the lead editor of several technical publications for the collaboration including the experiment's main technical publication on the experiment. Band and Heeger are also working on a review article on Daya Bay by Reviews of Modern Physics.

Postdoctoral researcher Langford leads the regular AD monitoring and target mass measurements, serves as co-chair of the target proton working group, and coordinates the overall analysis effort of the Yale group.

Graduate students Christine Lewis and Michael McFarlane successfully completed their dissertation work and defended in Spring 2014. Graduate students Lewis developed much of the software tools for the handling of the power data and the reactor flux predictions and developed the first reactor flux and spectrum predictions in the US based on the power plants operations data. Here thesis analysis focused on the measurement of the absolute reactor antineutrino spectrum at Daya Bay. Day Bay has collected >250k antineutrino events in the near-site detectors. With its unprecedented statistics and world-leading precision Daya Bay has provided a high-precision measurement of the reactor antineutrino spectrum revealing yet unseen spectral features. The measurement of the reactor spectrum and predictions are expected to be published in 2014. McFarlane's dissertation work was an independent oscillation analysis of the Daya Bay 6-detector data set using both rate and shape information. A deficit in the measured reactor antineutrino flux and a distortion in the observed energy spectrum are key signatures of neutrino oscillations. Graduate student McFarlanes performed an independent determination of θ_{13} and Δm^2_{ee} from a spectral analysis of the near and far site data. His work extended the initial Daya Bay rate-only analysis to the spectral shape and demonstrated evidence for reactor antineutrino oscillation based on the spectral shape alone.

Over the last few years Heeger's group has led several technical and scientific publications on the Daya Bay experiment and made significant contributions to its main results [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. The recent work supported by this award continues this effort. Publications resulting form this award are listed in Appendix 2.

3.2 PROSPECT: A Precision Oscillation and Spectrum Experiment

Anomalous results from a variety of neutrino experiments, astrophysical observations, and cosmology have revealed apparent inconsistencies with the Standard Model of three neutrinos [18]. Within the neutrino sector, these anomalies include event excesses in the data recorded by the LSND and MiniBooNE beam experiments, a rate deficit in source calibrations of radiochemical solar neutrino experiments, and an apparent deficit in the measured reactor antineutrino fluxes at short baselines of $\mathcal{O}$(10-100m), called the "reactor anomaly." These anomalies may be the signature of additional sterile neutrino states with mass splittings of the order of 1 eV^2 or unexplained experimental effects including unaccounted backgrounds or experimental artifacts. The apparent concordance of several experiments spanning a range of different sources, oscillation channels, and energies is difficult to ignore and an experimental test of the anomalous data with definitive resolution of the current situation is warranted. To address the "reactor anomaly" a compelling experimental approach is to make a precision measurement of the reactor antineutrino energy spectrum at distances comparable to the implied sterile neutrino oscillation length of $\mathcal{O}$(3m) and search for possible oscillation effects. The experimental approach of a short-baseline reactor experiment was discussed by Heeger et al. in [19, 20]. This experimental approach requires compact reactor cores of <1m as found in research reactors to avoid a washout of the oscillation effect. By studying spectral distortions as a function of baseline we can search for short-baseline oscillation effects independent of any absolute flux measurement and uncertainties in the reactor flux predictions. A reactor experiment at very short baselines offers the opportunity to directly search for oscillations over a distance of 4-25 m, makes a high-precision measurement of the reactor $\overline{\nu}_e$ spectrum, and tests models of reactor flux calculations by comparing the measured and predicted spectrum, and develops detector technology for reactor monitoring. US research reactors under consideration operate with highly enriched uranium (HEU) fuel. A benchmark measurement of an isotopically static HEU core will provide constraints on theoretical reactor antineutrino flux predictions, and therefore provides the opportunity to better understand the time variation of $\overline{\nu}_e$ spectra at conventional reactors with low-enriched uranium (LEU) fuel, supporting national safeguards applications.

Experimental challenges for a short-baseline reactor experiment include background rejection in detectors operated near a reactor and without significant overburden, energy calibration for a precision measurement of the spectral shape, and control of detector systematics. Careful detector and shielding designs are required. Efforts are underway to validate the shielding and detector design through R&D at potential host reactor sites. The National Institute of Standards and Technology (NIST), Oak Ridge National Laboratory (ORNL), and Idaho National Laboratory (INL) operate powerful, highly compact research reactors and have identified potential sites for the deployment of one or multiple compact antineutrino detectors at distances between 4-20m from the reactor cores. These reactors sites have agreed to siting detectors near their core and offer the opportunity for one of the shortest baseline measurements ever. Figure 2 shows the experimental concept of the proposed experiment at HFIR as well as the experiment's ability to map out oscillations in L/E space. Two detectors located at 4m and ~20m from the reactor can probe the preferred parameter space allowed by the "reactor anomaly" at 3σ in 1 year or 5σ in 3 years.

The proposed experiment will proceed in 2 phases: The objective of the first phase is the development and successful operation of a segmented $\overline{\nu}_e$ detector at the closest possible distance

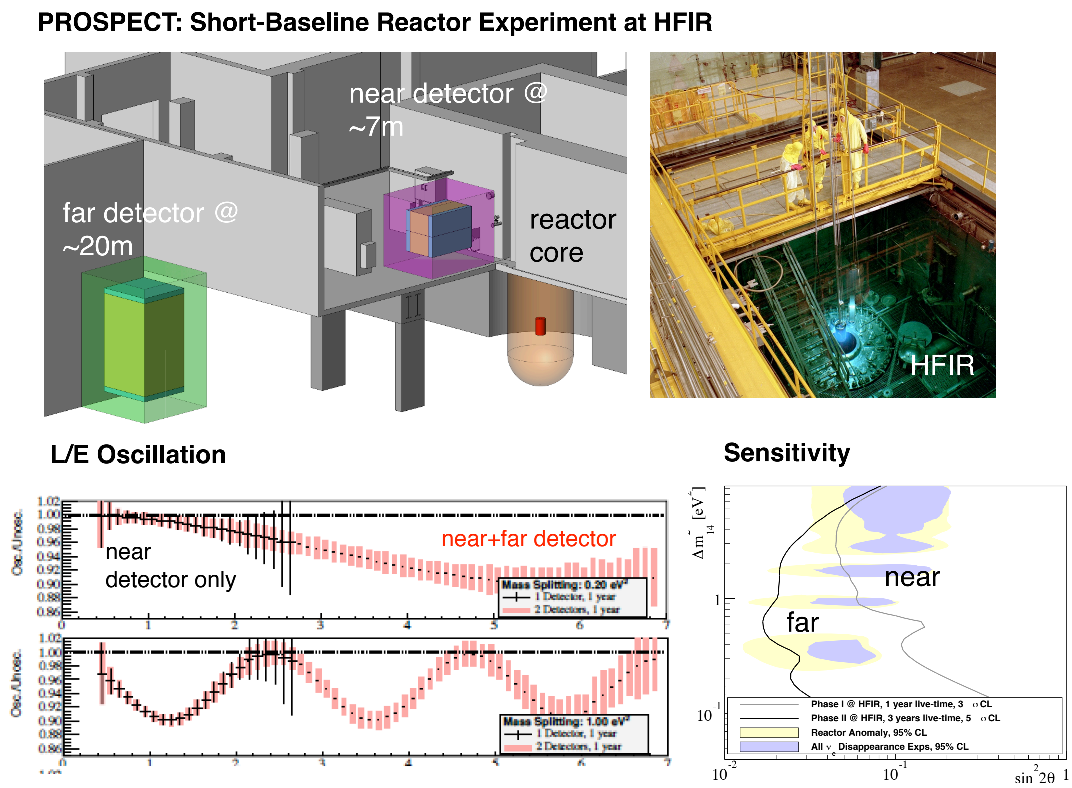

Figure 2: Top left: Concept of a 2-detector short-baseline experiment at the HFIR research reactor at ORNL. Top right: HFIR at ORNL. Bottom left: L/E oscillation signal for a near+far detector arrangement. Bottom right: Sensitivity of an experiment with near and/or far detectors at 3σ for 1 year of data [19, 20].

from a research reactor. This near detector will measure the reactor $\overline{\nu}_e$ spectrum in the background environment of a reactor. It is a technical demonstration of the detector technology and required background rejection. At the same time this detector will probe the favored parameter space of the "reactor anomaly" at 3σ in 1 live-year. The second phase of PROSPECT will add a larger detector at 15-25m to cover the complete allowed parameter region in 3 years at 5σ. See Figure 2.

Progress& Results

Over the past two years the Yale group in collaboration with LLNL has led the formation of a collaboration for a short-baseline reactor experiment in the US, called PROSPECT [2]. The goal is to deploy a ton-scale test detector at a research reactor and measure the reactor antineutrino spectrum at <10m from a reactor core. The collaboration includes groups with extensive experience in reactor neutrino physics including BNL, Chicago, Cincinnati, Drexel, LLNL, Wisconsin, and William&Mary. The specific activities of the Yale group focus on the development of the overall experimental strategy as well as developing and prototyping the design of the segmented, active target region of a ton-scale detector. This activity builds on the extensive experience of Heeger's group with the Day Bay and KamLAND scintillator detectors. In addition the Yale group has played a key role in the study and characterization of the reactor sites. Heeger has coordinated the formation of a PROSPECT collaboration, initiated and coordinated initial R&D activities, and together with colleagues from LLNL and NIST is co-leading the group towards the development of a full experimental proposal and technical design report.

Senior scientists Band is the R&D coordinator and interim project manager of the collaboration and provides the oversight and coordination at the reactor facilities. Band has spent significant effort at the reactor sites coordinating background measurements, assessing the site logistics, and interfacing the PROSPECT collaboration with the technical teams of the reactor sites.

Postdoctoral researcher Thomas Langford is leading the scintillator characterization and development and the setup of a test stand at Yale for the characterization of detector segments. The experiment plans to use novel Li-doped scintillator. Initial R&D results are very encouraging. Langford's work has been critical in establishing the viability of Li-doped scintillator for the experiment.

A collaboration meeting was held at Oak Ridge in October 2014. The collaboration communicates in several weekly phone calls on critical R&D and technical issues for the experiment. The next collaboration meeting is planned in September 2014.

Background Studies: The principal experimental challenge of the proposed short-baseline experiment is the operation of $\overline{\nu}_e$ detectors on-surface without significant overburden in the background environment of a research reactor. To establish feasibility and understand design constraints detailed background studies were performed at three US reactor sites: NIST, HFIR, and ATR. Figure 3 shows measurements of the gamma and neutron backgrounds at the NIST and HFIR reactors. Using both commercial as well as custom-developed neutron, gamma, and muon detectors a complete set of background measurements was performed at three reactor sites under consideration. The on-site background measurements were led by Senior Scientist Band and supported by postdoc Langford. The background measurements are now used by the collaboration as an input to detector simulations and optimizations of the required detector shielding. The background measurement and on-site studies were summarized in a comprehensive internal technical document. Based on this study the collaboration selected HFIR at ORNL as the default location for Phase I of the PROSPECT experiment.

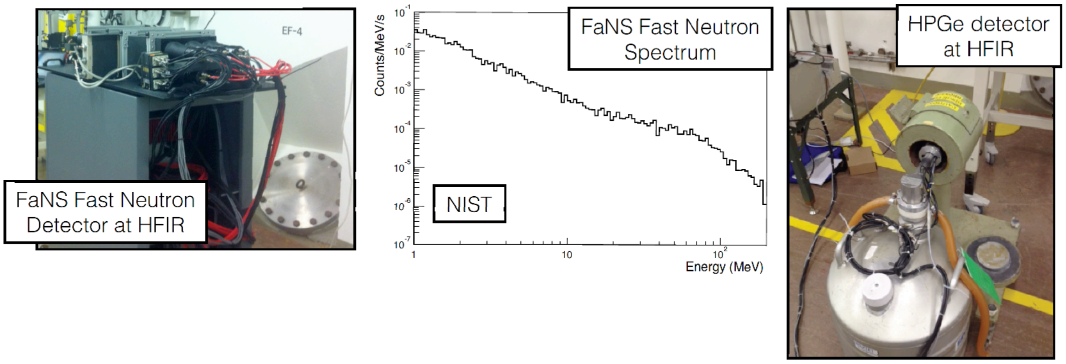

Figure 3: Neutron and gamma measurements at the NIST, ATR, and HFIR reactors. Portable instrumentation for the measurements provided by Yale, LLNL, and NIST were used in this work. The fast neutron spectrum was measured by Yale postdoc Thomas Langford with the FANS detector from NIST/UMD.

Detector Design and Prototype Construction: Reactor $\overline{\nu}_e$ are commonly detected through the inverse beta-decay reaction with the resulting positron and neutron coincidence signature. An advanced, segmented detector design, with novel ^{6}Li -doped scintillator for efficient neutron detection and event-by-event background rejection is under development by the PROSPECT collaboration. This will enable a precise measurement of the reactor spectrum in the background environment of a research reactor. During the time of this award the Yale group has played a leading role in the design of such a detector. Together with engineers from UW PSL the Yale group developed an integrated concept for a segmented detector, integrated a calibration system, and studies the assembly and installation of such a detector at HFIR. To benchmark simulations and characterize the performance of the scintillator we have constructed and characterized several test detector modules filled with Gd-doped and ^{6}Li-doped liquid scintillator at Yale University. These test detector modules are tested and calibrated at the Yale Wright Laboratory using available AmBe neutron and gamma sources. Various gamma and neutron shielding configurations have been assembled. Test detector modules are operated under various shielding configurations to understand the scintillator performance from data and benchmark against simulations. Figure 6 illustrates the concept of a modular, segmented scintillator detector with double-ended PMT readout per module. This design concept is now integrated with the reactor site and other site and logistics requirements.

Scintillator Development: Reactor $\overline{\nu}_e$ are detected through the inverse beta-decay reaction. The coincidence signature of the positron and neutron can be utilized to identify $\overline{\nu}_e$ candidates. Doped scintillators allow one to capture neutrons with high efficiency creating distinct signatures for event identification. Gd-doped scintillator, like the one used on Daya Bay, yields 8 MeV of gamma following 28 μs after a prompt event. These gammas can leak into the neighboring cells of a segmented detector. To improve background rejection and event identification within a single cell a novel Li-doped scintillator is under development yielding an α and triton from the neutron capture on ^{6}Li. Yale, BNL, and NIST are jointly developing and characterizing several formulations of Li-doped scintillator. At Yale postdoc Langford is characterizing

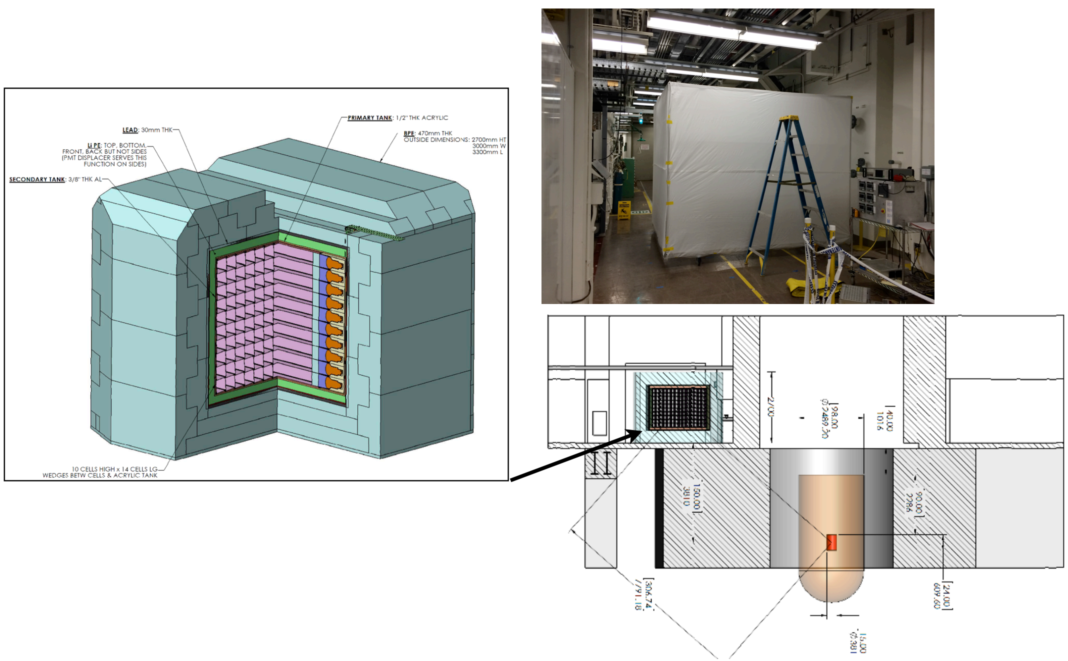

Figure 4: Design concept of a segmented scintillator detector inside passive shielding at the HFIR reactor. Left: The inner detector consists of liquid scintillator cells with low-mass optical dividers and double ended PMT readout. The passive shielding is an arrangement of several layers of gamma and neutron absorbing materials. Right Top: Mockup of the dimensions of the detector assembly at HFIR. Right Bottom: Elevation view of the position of the detector with respect to the HFIR reactor core. The detector will be located at a distance of about 7 m from the HFIR reactor core.

the pulse shape discrimination performance and light yield of the scintillator using prototype detector cells and test setups. See Figure 5.

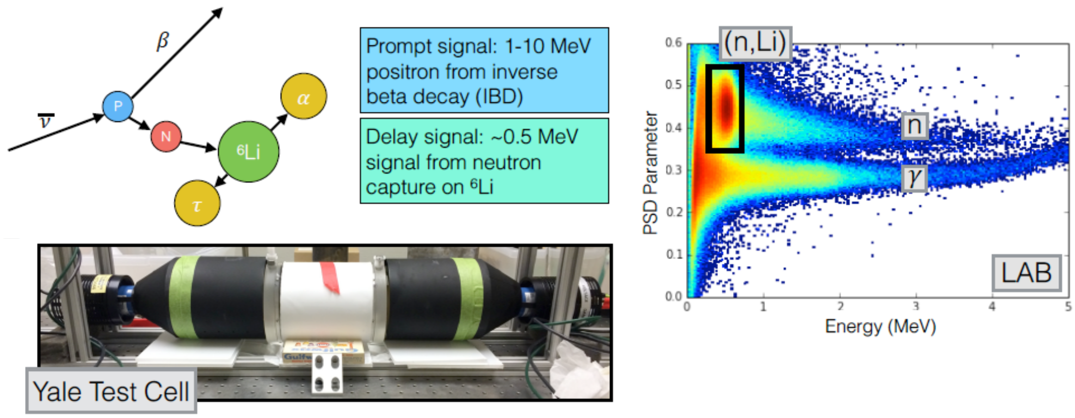

Figure 5: Testing and characterization of Li-doped scintillator at Yale for antineutrino detection. Right: Data of the pulse shape discrimination (PSD) vs energy for Li-doped scintillator using a neutron source. Bottom Left: One of the test cells used at Yale University for the characterization of the liquid scintillator.

Analysis of the Reactor Spectrum: Yale postdoctoral fellow Tom Langford together with Dan Dwyer from LBNL have studied reactor flux calculations to understand the spectral shape of the reactor antineutrino spectrum measured in Daya Bay and other θ_{13} experiments. Using available nuclear data they developed a model that qualitatively explains the spectral shape in the 4-6 MeV region of the spectrum. Their work offers an explanation for the observed spectral distortions and has been submitted for publication [5]. Future short-baseline experiments at research reactors such as PROSPECT will provide the opportunity to measure the spectrum of a HEU reactor core and compare it to the spectrum from a commercial reactor such as Daya Bay.

4 Synergistic Activities

Professor Heeger is a member of the High Energy Physics Advisory Panel (HEPAP) and has been involved in the community planning process leading to the P5 report. He was one of the conveners for the study group on underground laboratories, he co-authored the neutrino working group report, and presented a summary of present and future reactor neutrino experiments at the P5 community town meetings. Heeger is an Associate Editor for European Physics Journal C and Journal of Physics G. He is a regular reviewer for Physical Review and other Journals.

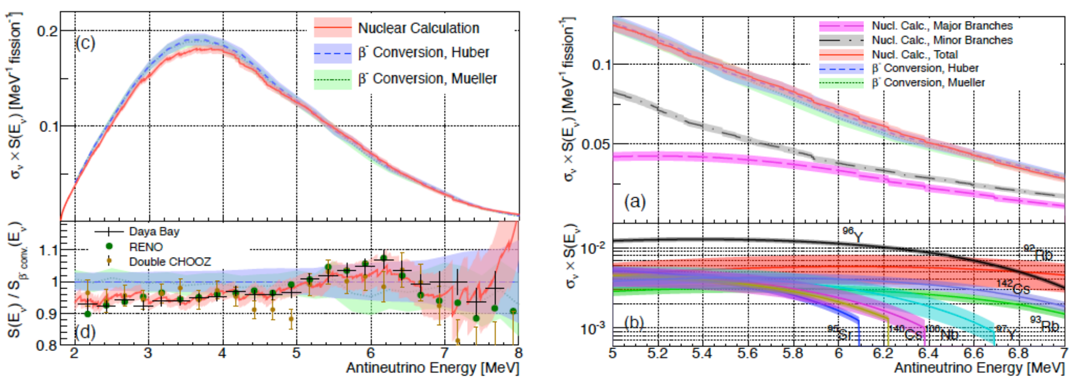

Figure 6: Ab initio nuclear calculation of the cumulative β^- energy spectrum per fission of ^{235}U exposed to thermal neutrons (solid red), including due to fission yields and branching fractions. Antineutrino spectrum per fission in a nominal reactor weighted by the inverse beta decay cross section (solid red), compared with that obtained by the β^- conversion method. Figures from arXiv:1407.1281 and private communication. Submitted for publication.

Appendix 1: Student Education

Student's Name	*Date Entered Graduate School*	*Date* Joined Group	Degree Program	*Date Degree Expected*	*Advisor*
Michael McFarlane	Sep 2006	Jan 2008	Ph.D.	May 2014	K. Heeger
Christine Lewis	Sep 2006	Jun 2008	Ph.D.	Feb 2014	K. Heeger
Danielle Norcini	Sep 2013	May 2014	Ph.D.	2018	K. Heeger

Table 1: Two graduate students graduated during the period of this award. Michael McFarlane and Christine Lewis successfully defended their dissertations at the University of Wisconsin in Spring 2014. Yale graduate student Danielle Norcini joined the group in Spring 2014 and is now working on R&D for PROSPECT and data analysis for Daya Bay.

Appendix 2: Publications From This Award

References

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