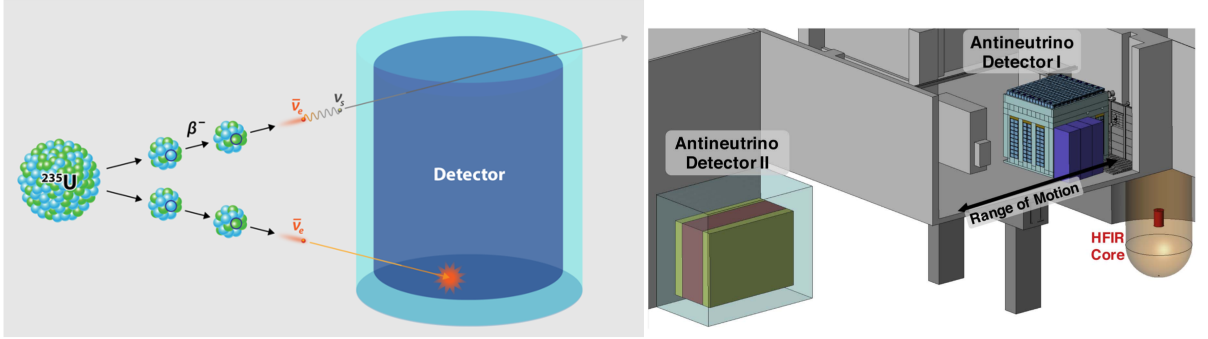
Reactor Modeling Uncertainties for Antineutrino Detection at HFIR Using the PROSPECT Experiment

Andrew Conant[1], Nathaniel Bowden[2], Anna Erickson[1]
on behalf of the PROSPECT Collaboration
[1]Georgia Institute of Technology, [2]Lawrence Livermore National Laboratory

Introduction

PROSPECT, the Precision Oscillation and Spectrum Experiment [1], is measuring the antineutrino flux at the High Flux Isotope Reactor (HFIR), a research reactor at Oak Ridge National Laboratory (ORNL). PROSPECT will be making the first modern measurement from antineutrinos at a highly-enriched uranium reactor at a short baseline, within 10 meters, from the core (Fig. 1b). PROSPECT uses a 4-ton ^{6}Li-doped, segmented liquid scintillator detector to measure neutrino oscillations and test the hypothesis of an existence of a fourth type of neutrino, the "sterile" neutrino. Antineutrinos are products of beta transmutations of neutron-rich fission products; their detection relies on the inverse beta decay reaction:

$$\bar{\nu}_e + ^1_1p \rightarrow ^1_0n + \beta^+ \qquad (1)$$



(a) (b)

Figure 1: Schematic of antineutrino detector (a) and layout of the PROSPECT experiment [1] at short baseline to the HFIR core (b)

Some challenges still exist in recent antineutrino experiments. First, the antineutrino yield and spectrum from conversion of beta spectra measurements [2] differs between the four major fissile isotopes, so the evolution of the antineutrino flux from a reactor depends on the reactor and fuel design (Fig. 3a). The recent Daya Bay experiment has found that the reactor flux predictions of ^{235}U are incorrect [3]. Second, neutrino experiments have experienced a consistent 4-8% deficit in the observed-to-predicted ratio of antineutrinos from a reactor, called the reactor antineutrino anomaly [4], and a bump in the 4-6 MeV range (Fig. 3b [5]). Oscillations at short-baseline studies may indicate the existence of a sterile neutrino. The current PROSPECT collaboration will contribute knowledge in these areas by measuring the nearly pure ^{235}U spectrum at short baseline.

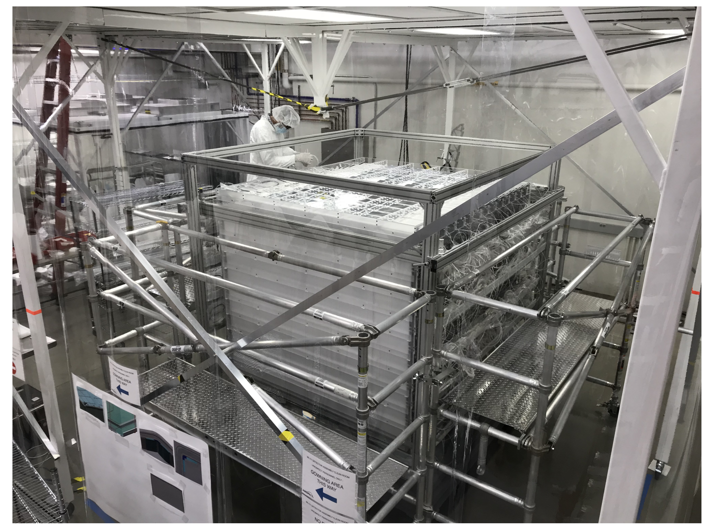
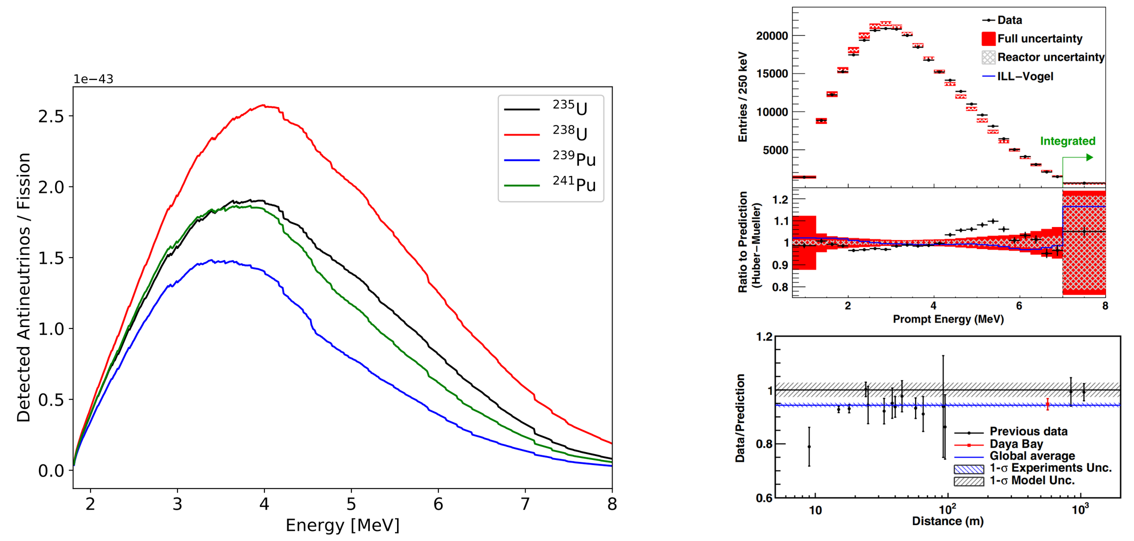


Figure 2: Construction of the PROSPECT antineutrino detector (AD) at Yale University



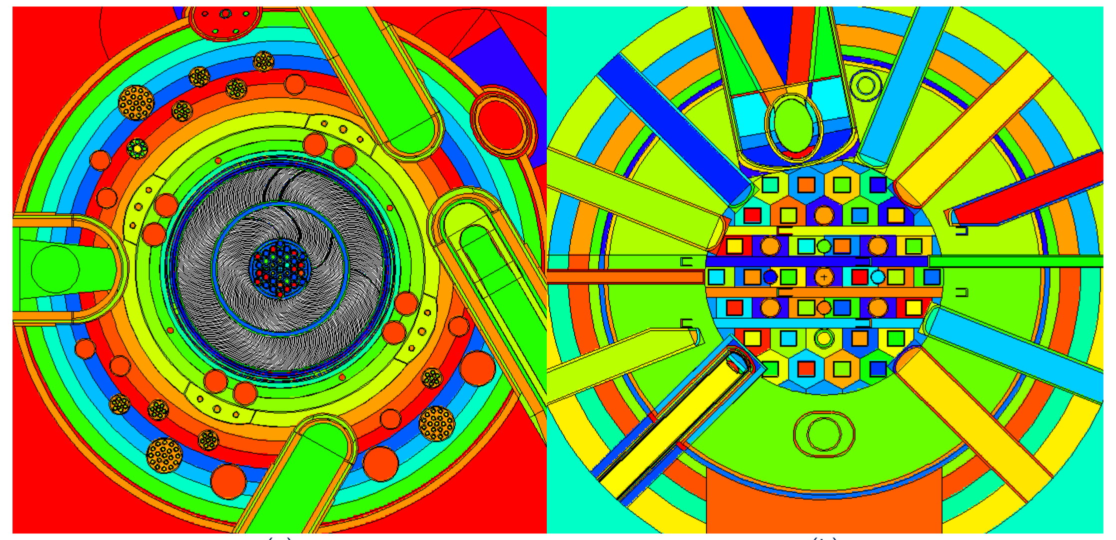
(a) (b)

Figure 3: Spectrum and relative magnitude of the four main fissile isotopes (a) and predicted vs. measured fluxes realing a bump [top and midde panes] and deficit of the antineutrino anomaly [bottom pane] (b) [5]

Current neutrino experiments require reactor modeling to predict fission rate and fractions. The objective of this work is to quantify fission fractions and uncertainties in the reactor for the PROSPECT experiment. Future implications of this work are in the development and implementation of antineutrino detectors for safeguards and nonproliferation applications.

Modeling & Simulation

- HFIR is modeled in MCNP [6] due to extensive benchmarking of HFIR model [7]
- Comparison with two other reactors, the NBSR and PWR
  - NBSR: National Bureau of Standards Reactor (HEU reactor with similar fuel design) [8]
  - PWR: Pressurized Water Reactor (commercial reactor at which other antineutrino experiments have taken place) [9]



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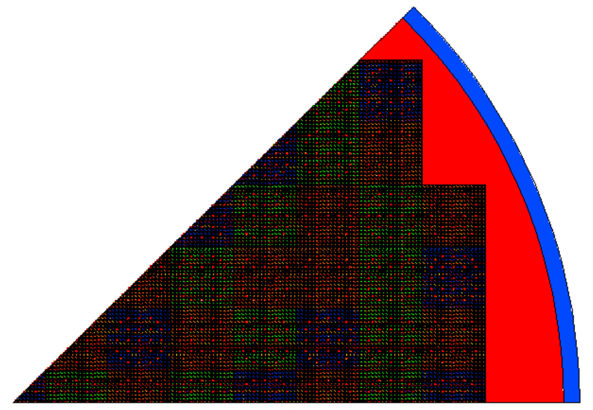


(c)

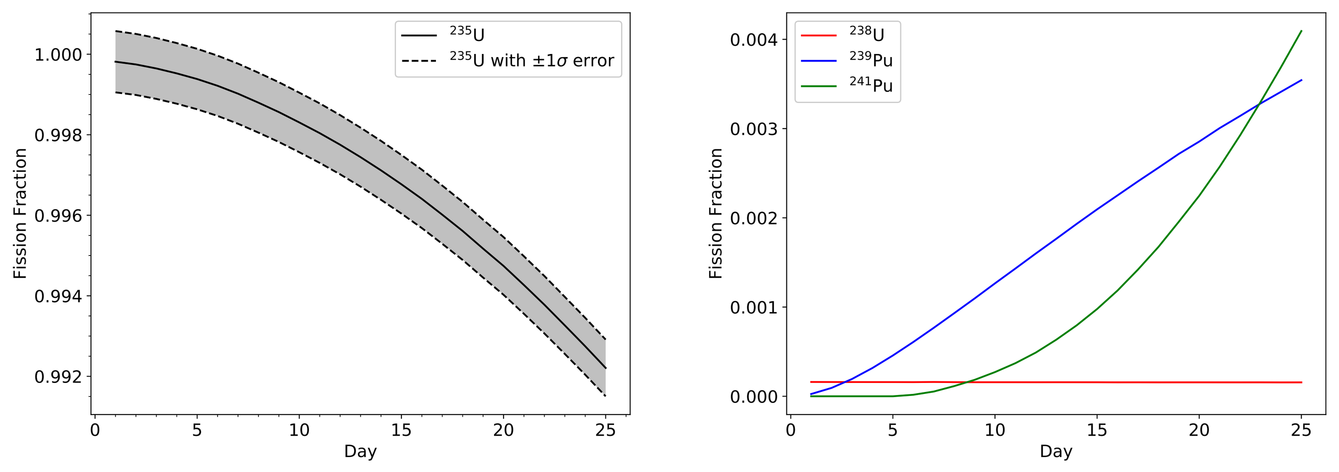
	HFIR	NBSR	PWR
Power (MW)	85	20	3565
Cycle Length (days)	24	35	540
Core Height (m)	0.45	0.74	3.76
Core Radius (m)	0.61	1.22	3.66
Fuel Type	U_3O_8-Al	U_3O_8-Al	UO_2
^{235}U Enrichment (%)	93	93	3-5
Moderator	H_2O	D_2O	H_2O
Fuel Element	Plate	Plate	Rod
Fuel Element Grouping	Element	Assembly	Assembly

(d)

Figure 4: MCNP models of HFIR [7] (a), NBSR [8] (b), PWR [9] (c), and table of nominal operating parameters of the reactors

Fission Fractions in HFIR

- MCNP tallies calculate isotope-specific reaction rates using fission mutlipliers for "phantom" materials
- ^{235}U stays above a fission fraction of 0.99 throughout the cycle
- ^{238}U remains constant, but ^{239}Pu and ^{241}Pu increase up to about 0.4% by the end of cycle

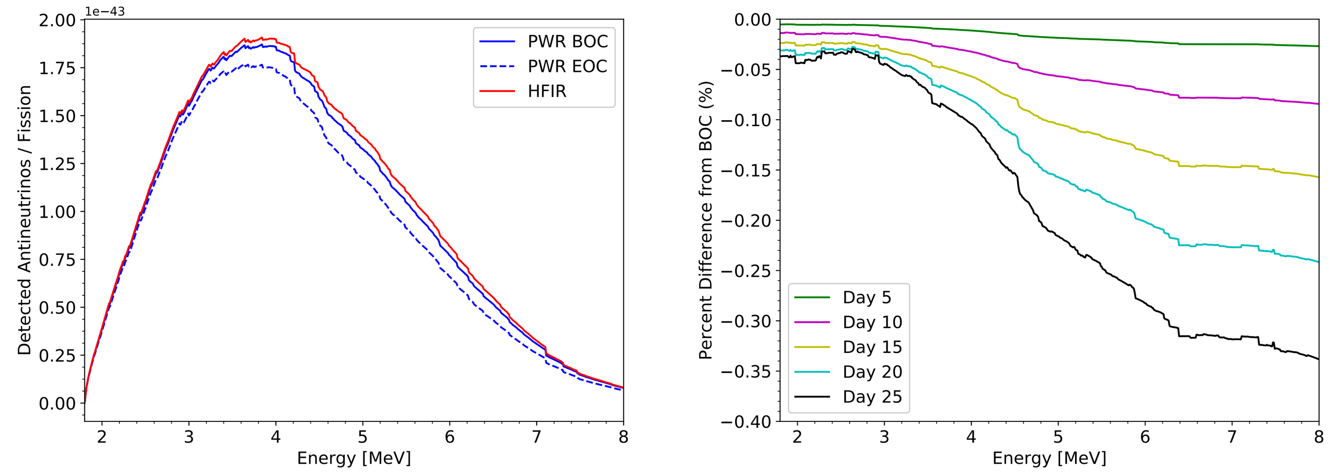


(a) (b)

Figure 5: Fission fraction of ^{235}U by day in the HFIR cycle (a) and for the other three fissile isotopes (b). Note that error bars are not shown for the latter due to being small compared to the data

Antineutrino Spectra

- Fission rates are converted to antineutrino spectra with Python-based Oklo toolkit [10] using ENDF/ENSDF
- PWR spectrum changes significantly due to large (>30%) fission fraction of ^{239}Pu at the end of cycle (Fig. 6a)
- HFIR sees a decline in high energy bins of no more than 0.4% (Fig. 6b)

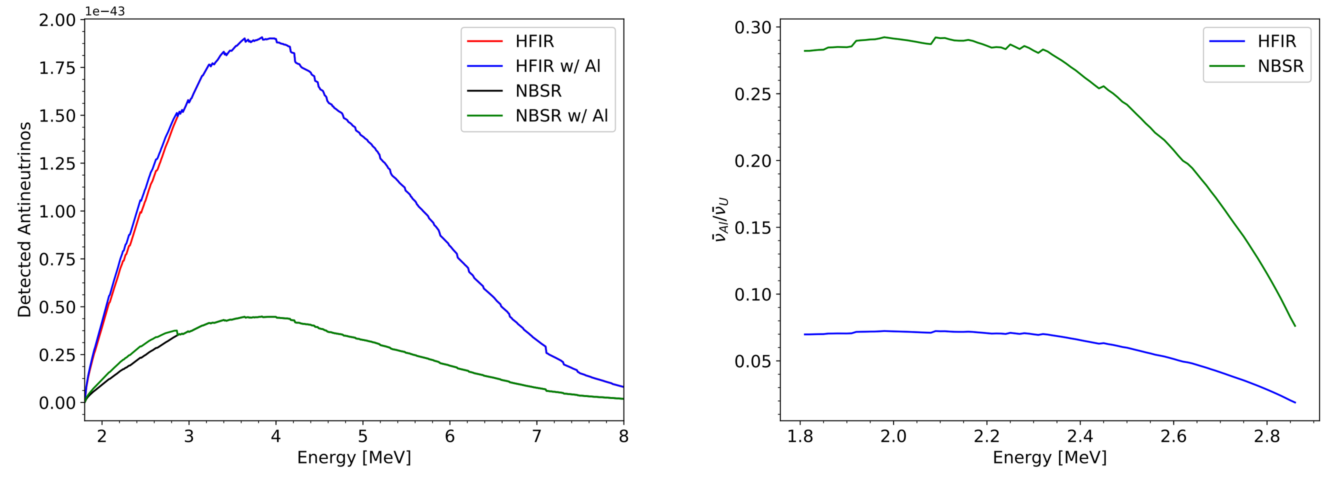


(a) (b)

Figure 6: Spectra of detected antineutrinos per fission for the beginning and end of cycle for a PWR compared to that of HFIR (a) and the percent difference in each energy bin for HFIR relative to beginning of cycle (b)

Non-Fission Sources of Antineutrinos - Aluminum

- Activation of aluminum can generate antineutrinos above the IBD threshold
- Despite similar design, NBSR sees larger activation-to-fission ratio and therefore larger bump (Fig. 7a)
- NBSR has nearly three times as many excess antineutrinos at low-energy range (Fig. 7b)
- Difference is not due to neutron spectra but due to fuel geometry and localized activations (Fig. 7c-7d)



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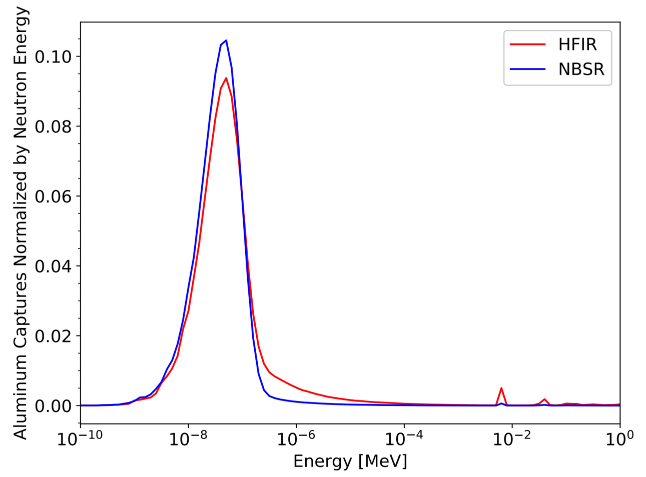


(c)

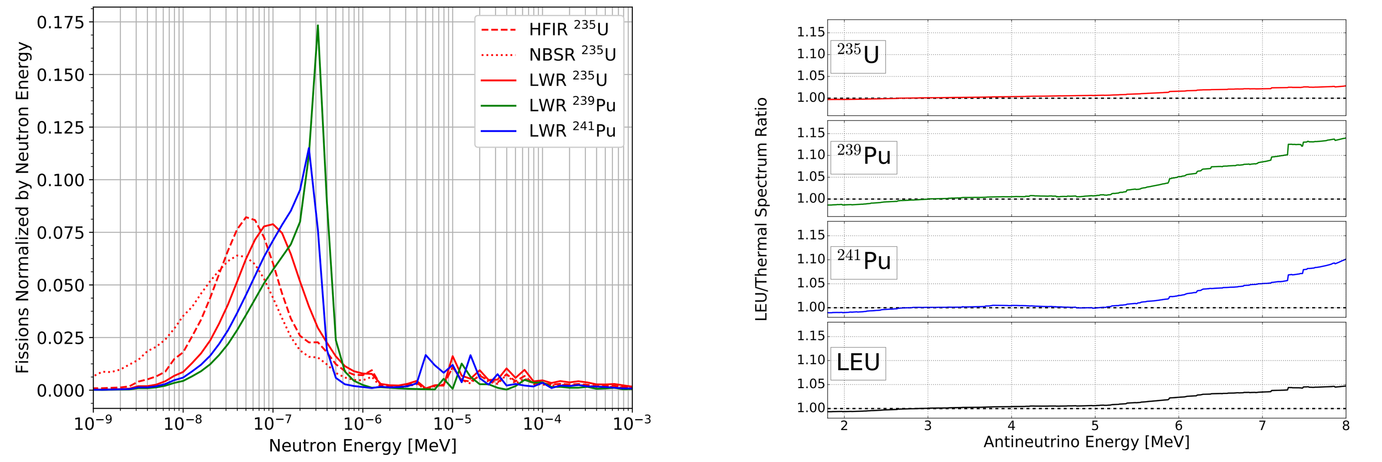
Structural Category	HFIR	NBSR
Core Structural	39.92%	56.19%
Beam Tube	18.81%	9.24%
Reflector	17.47%	5.67%
Control Elements	10.88%	13.23%
Fuel	7.42%	1.96%
Fuel Filler/Clad	5.50%	13.70%

(d)

Figure 7: Comparison of antineutrino spectra from HFIR and NBSR with and without aluminum activation (a), the non-fission excess antineutrinos aluminum contributes (b), and energy spectra and regional distribution of aluminum captures in both cores (c,d)

Impact of Fission Neutron Energy: Case Study

- One hypothesis is the treatment of fissions from epithermal neutrons may help explain the anomaly [11]
- Reactor simulations & fission yield database treatment create binding cases for epithermal treatment
- Propogated differences in antineutrino spectra suggest that neutron energy is unlikely to cause anomaly [12]



(a) (b)

Figure 8: Energies of fission inducing-neutrons (a) and the propogation of that uncertainty to antineutrino spectrum differences compared to that of a PWR mixed spectrum (b) [12]

Conclusions

1. Reactor modeling efforts can aid current experiments in reducing uncertainty in the antineutrino production
2. Models confirm and quantify variation in fission fractions & antineutrino flux in the HFIR core
3. Non-fission sources of antineutrinos (aluminum) may contribute significantly to increased flux at low energies
4. Modeling has helped discredit the neutron energy hypothesis of the reactor antineutrino anomaly

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Acknowledgements

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