First results from the PROSPECT reactor neutrino experiment

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on behalf of the PROSPECT collaboration

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Nuclear reactors: tools for discovery

Savannah River, 1956
first observation of (anti)neutrinos

KamLAND, 2003
discovery of antineutrino oscillation
measurement of geoneutrinos

DYB, DC, RENO, 2012
precision measurement of $\theta_{13}$

what can future reactor experiments tell us about neutrinos?
Generation of reactor antineutrinos

- fission produces neutron-rich daughters that beta decay ~6 times until stable
- $1 \text{ GW}_{\text{th}} \sim 10^{20} \overline{\nu}_e/\text{second}$
- $>99.9\%$ flux $\overline{\nu}_e$ - only from this process
- number and average energy of $\overline{\nu}_e$ dependent on parent fission nuclei

- power reactors (LEU) have low enriched uranium cores: $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$
- research reactors (HEU) have high enriched uranium cores: $^{235}\text{U}$ only

reactors are a pure, prolific source of neutrinos dependent on isotopic content
Predicting the antineutrino flux and spectrum

Two major approaches used:

1. *Ab-initio*
   - sum the spectrum from thousands of beta branches using nuclear databases
   - databases incomplete and large uncertainties

\[
S(E_{\bar{\nu}}) = \sum_{i=0}^{n} \sum_{j=0}^{m} R_i f_{ij} S_{ij}(E_{\bar{\nu}}).
\]

2. Beta conversion
   - empirical measurements of beta spectra for each isotope (foils, 1980's)
   - fit with ‘virtual branches’ and kinematically convert to antineutrino spectra


*predicting reactor spectra is complicated*
Reactant antineutrino flux deficit

- $\Theta_{13}$ also measure the flux experiments at near detectors and compare to model
- when comparing all reactor experiments to model, shows ~6% flux deficit
- model issues or is there a particle physics solution?
- sterile neutrinos would have major implications on neutrino physics/cosmology

**flux disagreement - does an eV-scale sterile exist?**
\( \theta_{13} \) antineutrino spectral deviations

- all \( \theta_{13} \) experiments observe deviations throughout the spectrum, prominent excess 4-6 MeV prompt energy (5-7 MeV neutrino energy)
- cannot be explained by a sterile neutrino
- tracks with reactor power (LEU power), appears in near and far detectors
- most likely an issue with nuclear models - one, some, all isotopes?

**spectrum disagreement - do we model all of the fissile isotopes correctly?**
The Precision Reactor Oscillation and SPECTrum experiment
Precision Reactor Oscillation and SPECTrum experiment

**Scientific Goals:**
1. search for very short baseline oscillations from eV-scale sterile neutrinos
2. measure $^{235}\text{U}$ antineutrino spectrum to address spectral deviations

**Experimental strategy:**
- measure energy spectrum at a range of baselines (7-9m in closest position)
- model-independent search for oscillations within segmented detector
- high statistics, high resolution $^{235}\text{U}$ spectrum measurement

**Challenges:**
- minimal overburden (< 1mwe) in high background environment

@ High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory
Neutrino source: High Flux Isotope Reactor @ ORNL

- 85MW highly enriched uranium reactor
- >99% of $\nu$ from $^{235}$U fissions, effectively no isotopic evolution
- compact core (44cm diameter, 51cm tall)
- 24 day cycles, 46% reactor up time
- detailed study of surface cosmogenic backgrounds (PROSPECT: NIMA A806 (2016) 401)

Reactor Sizes

Core replacement

HFIR site

Power density

Relative Power (arb.)

0.0
0.2
0.4
0.6
0.8
1.0

-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

$\pm 0.1$ $\pm 0.2$ $\pm 0.3$ $\pm 0.4$ $\pm 0.5$ $\pm 0.6$ $\pm 0.7$ $\pm 0.8$ $\pm 0.9$ $\pm 1.0$

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Yale Weak Interactions Discussion Group Seminar: 06 November 2018

Yale University
Experimental strategy at HFIR: oscillations

- oscillations modify energy spectrum as a function of baseline
  \[ P_{a \rightarrow b} \sim \sin^2(2\theta_{ab}) \sin^2 \left( 1.27 \frac{\Delta m_{ab} L}{E} \right) \]
- segments allow measurements at different baselines
- compare segment spectrum shape to full detector spectrum for model-independent sterile search
Realization of experiment strategy:

- **target/detection:** $^6$Li-loaded liquid scintillator
- 154 segments, $119\text{cm} \times 15\text{cm} \times 15\text{cm}$
- thin (1.5mm) optical panels held in place by 3D printed support rods
- 25 liters/segment, **total mass:** $\sim 4$ tons
- segmentation enables:
  - calibration access throughout volume
  - 3D position reconstruction ($X$, $Y$) with ($Z$) from double-ended PMT readout
  - fiducialization
  - optimized shield for cosmogenics
Detection with $^6$Li-loaded liquid scintillator

$E = 1-10$ MeV

- use workhorse inverse beta decay (IBD) detection interaction, correlated signal
- prompt energy: sum of positron ionization and 2x 511 keV annihilation gammas, proxy for neutrino energy
- compact detector needs a capture agent that is highly localized, within segments
- temporal and spatial cuts to identify IBDs and reject backgrounds

$\bar{\nu}_e + p \rightarrow \beta^+ + n$

$E \sim 0.55$ MeV

$\nu_e$
Pulse shape discrimination (PSD)

Even better handle on IBD acceptance and background rejection with particle ID. Takes advantage of different energy deposition densities for different particle types.

\[
\text{PSD} = \frac{Q_{\text{tail}}}{Q_{\text{full}}}
\]

PSD can identify particle type through shape of pulse
Roadmap: R&D of $^6\text{Li}$-loaded LS detectors

**PROSPECT-0.1**
Develop LS  
Characterize LS  
Aug 2014-Spring 2015
- 5cm length  
- 0.1 liters  
- LS, $^6\text{Li}$LS

**PROSPECT-2**
Background studies  
Dec 2014 - Aug 2015
- 12.5 length  
- 1.7 liters  
- $^6\text{Li}$LS

**PROSPECT-20**
Segment optics  
Background studies  
Spring/Summer 2015
- 1m length  
- 23 liters  
- LS, $^6\text{Li}$LS

**PROSPECT-50**
Performance validation  
Simulation benchmark  
2017-2018
- 1x2 segments  
- 1.2m length  
- 50 liters  
- LS,$^6\text{Li}$LS

**PROSPECT AD**
Physics measurement  
data taking 2018
- 11x14 segments  
- 1.2m length  
- 4 tons  
- $^6\text{Li}$LS

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Surface detector to combat backgrounds

- near-surface backgrounds: cosmogenic fast neutrons, reactor-related gammas
- power of segmented detector with $^6$Li liquid scintillator
- combination of PSD, shower veto, topology, and fiducialization cuts provide $>10^4$ active background suppression (signal:background $> 1$)

optimized detector design for background ID and suppression
Optical module assembly @ Yale Wright Lab

Modules in liquid volume: scintillator approved!

- Front reflector
- PMT
- Opaque acrylic housing
- Mineral oil
- Seal plugs
- Pusher plate
- Voltage divider
- UV transparent window

Cementing reflectors

Installing PMTs

Testing

November 2016-2017
Yale Wright Laboratory
Liquid scintillator was stored at BNL in 28 (55-gallon) drums. A temperature-controlled truck was used to transport the scintillator to Oak Ridge Nat. Lab. ISO tank filling mix all 6 LiLS drums into one tank. Antineutrino Detector filling February 2018 arrival at ORNL filling from mixing tank in position at HFIR first muon track.
Liquid scintillator was stored at BNL in 28 (55-gallon) drums. A temperature-controlled truck was used to transport the scintillator to Oak Ridge Nat. Lab. ISO tank filling mix all 6 LiLS drums into one tank. Antineutrino Detector filling FEBRUARY 2018 ARRIVAL AT ORNL FILLING FROM MIXING TANK IN POSITION AT HFIR SHOWER
Liquid scintillator was stored at BNL in 28 (55-gallon) drums. A temperature-controlled truck was used to transport the scintillator to Oak Ridge Nat. Lab. ISO tank filling mix all 6 LiLS drums into one tank in February 2018. Arrival at ORNL filling from mixing tank. IBD candidate.
Operation + Characterization

Reactor On 24 hours
Reactor Off
Reactor On - Reactor Off

Within a few hours.. 5σ neutrino signal!
Energy reconstruction

- ensure energy reconstruction is performing
- gamma sources deployed throughout detector, measure single segment and full detector response
- beta spectrum from proton PSD tagged $^{12}$B production for high energy calibration

- simultaneous fit to MC, response parameters
- full detector $E_{\text{rec}}$ within 1% of $E_{\text{true}}$
- high light collection: $795\pm15$ PE/MeV
- resolution includes geometric/dark current

**good energy reconstruction and resolution performance**

PROSPECT: arXiv:1806.02784
Energy stability and uniformity

Need to ensure reconstruction is uniform over the 154 segments and time…

- many calibration and distributed intrinsic sources to look at the data in different ways (e.g. $^{137}$Cs, BiPo $\alpha$'s, nLi)
- map energy response of each segment, uniformity $\sim 1\%$
- map energy response of each segment over time, stability $< 1\%$

energy reconstruction is stable throughout the detector over time
Pulse shape discrimination performance

- excellent particle ID of gamma interactions, neutron captures, and nuclear recoils
- dominant backgrounds: cosmogenic fast neutrons, reactor-related gamma rays
- vast majority identified and rejected by PSD for prompt and delayed signals
- tag IBDs with high efficiency and high purity

excellent pulse shape discrimination performance
• cosmogenic backgrounds are known to vary with atmospheric conditions
• reactor-off IBD-like candidates split into two periods
• consistent rate and spectrum observed, even up to 20MeV!
• features from muon induced showers (nH) and fast neutron scatters (nC*)
• essential cross-check for background subtraction

background selection stable in rate and spectrum over time
Search for
STERILE NEUTRINOS
Oscillation data set

- 33 days of **Reactor On**
- 28 days of **Reactor Off**

From 0.8-7.2 MeV prompt:
- 24,461 IBD interactions
- average of ~771 IBDs/day
- correlated S:B = 1.32
- accidental S:B = 2.20
- IBD event selection defined and frozen on 3 days of data

PROSPECT: arXiv:1806.02784

**best signal:background achieved for near-surface detector**
Oscillation search in baseline + energy

- observation of \(1/r^2\) behavior throughout detector volume
- 40% flux decrease from front of detector to back as expected
- 14 baseline measurements within the detector at a single location

PROSPECT: arXiv:1806.02784

- oscillations small over baselines
- energy+baseline (L-E) distribution provides greater sensitivity
Sterile neutrino sensitivity and exclusion

- compare measured L-E spectra to normalized full detector spectrum for each \((\Delta m^2, \sin^2 2\theta)\) to build \(\chi^2\)
- includes covariance matrices to capture all stat+sys uncertainties
- to determine confidence intervals use Feldman-Cousins approach
- generate \(\chi^2\) map for each \((\Delta m^2, \sin^2 2\theta)\) with PROSPECT-like toy MC
- 95% exclusion curve based on 33 days reactor-on operation
- direct test of the Reactor Antineutrino Anomaly

**PROSPECT: arXiv:1806.02784**

*first result: disfavors RAA best-fit point at >95% (2.2\(\sigma\))*
1. There are interesting problems to solve with reactor neutrinos, maybe new physics.

2. PROSPECT is a unique short baseline reactor experiment that has:
   • driven an extensive R&D program with $^{6}$LiLS scintillation detectors.
   • achieved world-leading signal:background for surface-based detector.

3. First oscillation analysis disfavors the RAA sterile neutrino hypothesis at 2.2σ.