PROSPECTs for Short-Baseline Oscillation Searches at Reactors

May 18, 2015

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PROSPECT20 Prototype in Shield at HFIR

PROSPECT20 Prototype at HFIR
The Reactor Antineutrino Anomaly

- Existing global deficit in measured antineutrinos at all baselines
  - Improved flux prediction based on method used for decades (beta conversion)
  - Interaction channel is well-understood (inverse beta decay)
  - Measurement agrees among variety of groups, reactors, detection techniques
- What’s going on??? Is the anomaly real? What is the cause?

![Graph showing N_{obs}/N_{exp} vs Distance to reactor (m)](image)

Do we have a ‘reactor antineutrino anomaly?’

- “No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time”

Daya Bay also sees the reactor flux deficit

- 5% deficit relative to 2011 Huber/Mueller flux prediction
- Blind analysis: No reactor power data available until analysis is totally fixed

Reference Model: Huber (3 isotopes) + Mueller (\(^{238}\text{U}\))

C. Zhang (Daya Bay), Neutrino 2014
Reactor Anomaly Explanations

• Do we have a ‘reactor antineutrino anomaly?’
  • “Yes: it’s probably attributable to problems in the beta-to-$\nu_e$ conversion”

• Spectra from $\theta_{13}$ experiments disagree with predictions
  • “If measured spectrum doesn’t match, why should measured flux?”

• See D. Dwyer’s talk tomorrow
Do we have a ‘reactor antineutrino anomaly?’

- “Yes: the deficit could result from short-baseline sterile neutrino oscillations”
- Consistent with existing nonzero hints for sterile neutrinos
  - LSND, MiniBooNE, Gallium
  - However, tension with null $\nu_\mu$ disappearance measurements
- Need more oscillation data at shorter baselines (smaller L/E)
SBL Oscillation Experiments at Reactors

- **Measure energy spectrum at each detector-reactor baseline**
- **Look for unexpected L/E distortion: oscillations**
- **Want to see L+E variation as sterile ‘smoking gun’**

\[
P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)} \right]
\]

Example: 3x1x1 m\(^3\) detector, 1 m\(^3\) 20 MW HEU core, 4m closest distance

**Oscillated:**
\[
\Delta m^2 = 1.8 \text{ eV}^2 \\
\sin^2 2\theta = 0.5
\]
What New Data Is Needed

• To get to the bottom of this puzzle, we need new data!
  • Really want to make short-baseline versions of the plots below

• In particular, we really need:
  • A high energy-resolution detector for precisely measuring absolute spectrum
  • A high position-resolution detector for comparing spectra between baselines
  • Any successful experiment will need excellent background rejection capabilities
Current SBL Reactor Efforts

- Wide variety of efforts SBL efforts worldwide
  - Variety of technologies achieve varying levels of position, energy resolution
  - All experiments in varying stages of R&D or prototyping
- Will focus on one illustrating case: PROSPECT
  - **Precision Reactor Oscillation and SPECTrum Experiment**
  - Excellent performance in both energy AND position reconstruction
  - Multi-faceted background reduction strategy

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<th>Good X-Res</th>
<th>Good E-Res</th>
<th>L Range (meters)</th>
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• High Flux Isotope Reactor (ORNL): $^{235}$U-only reactor with 42% up-time

• Extensive passive shielding

• Li-doped segmented liquid scintillator target region: ~3 tons for near detector (Phase I)

• Moveable: ~6.5-11 m baselines
**PROSPECT Neutrino Detection**

- Inverse beta interactions in Li-loaded EJ309 liquid scintillator
- 10 x 14 optically decoupled cells: ~15cm x 15cm x 100cm each
- Specularly reflecting cell walls quickly guide light to PMTs
- System can meet position/energy resolution requirements

**Calibration sources**

- **Prompt signal:** 1-10 MeV positron from inverse beta decay (IBD)
- **Delay signal:** ~0.5 MeV signal from neutron capture on $^6\text{Li}$
**PROSPECT Prototype Demonstrations**

- **Run DAQ, Remote data-taking**
- **See n-Li + PSD**
- **Demonstrate shielded background rates**
- **Demonstrate full timing and PE response**
- **Deploy final design concepts**
- **Observe relative segment responses**
- **See antineutrinos**
- **Oscillation physics**
- **Absolute spectrum**

* **Deployment complete!!!* 

**PROSPECT 0.1**
- Aug 2014
- See n-Li + PSD

**PROSPECT 2**
- Dec 2014 - Mar 2015
- 2 inches
- 5 inches

**PROSPECT 20**
- Mar 2015
- 1 meter

**PROSPECT 200**
- 3x3x1 meter mockup at IIT

**PROSPECT Phase I:**
- 1 detector, moveable

**PROSPECT Phase II:**
- 2 detectors

**PROSPECT Phase II:**
PROSPECT Prototype Demonstrations

- **Run DAQ, Remote data-taking**
- **See n-Li + PSD**
- **Demonstrate shielded background rates**
- **Demonstrate full timing and PE response**

**PROSPECT 0.1**
- Aug 2014
- **✓**

**PROSPECT 2**
- Dec 2014 - Mar 2015
- **✓**

**PROSPECT 20**
- Mar 2015
- **✓**

**PROSPECT 200**
- **✓**

**PROSPECT 2000**
- 3x3x1 meter mockup at IIT
- **✓**

**PROSPECT Phase I:**
- 1 detector, moveable
- **✓**

**PROSPECT Phase II:**
- 2 detectors
- **✓**

*Deployment complete!!!!*

- ** Approximate mass kg**
- ** Oscillation physics**
- ** Absolute spectrum**

**PROSPECT Prototype Demonstrations**

- **PROSPECT Phase I:**
  - 1 detector, moveable
  - **✓**

- **PROSPECT Phase II:**
  - 2 detectors
  - **✓**

* Deployment complete!!!!!!*
Demonstrating Key Requirements

• To accomplish physics goals, a SBL reactor experiment needs:
  • Understanding of energy scale and energy and position resolution
  • Control of backgrounds at on-surface near-reactor location

• Prototyping program will demonstrate PROSPECT’s abilities in all of these areas.

PROSPECT20 meter-long cell at HFIR

PROSPECT20 at HFIR in full shielding package
Background Rejection, Signal Selection

- Reduce backgrounds: Li-capture and pulse-shape discrimination

**Signal, Main Backgrounds**

- Inverse Beta Decay
  - $\gamma$-like prompt, $n$-like delay
  - Fast Neutron
- $n$-like prompt, $n$-like delay
- Accidentals
  - $\gamma$-like prompt, $\gamma$-like delay

**Equation**

$$PSD = \frac{Q_{\text{tail}}}{Q_{\text{full}}}$$

**Graphs**

- Normalized template pulse vs. time (ns)
- Scatter plot of energy vs. PSD parameter
- Heatmap of PSD vs. prompt PSD

**Figures**

- Fig. 9
- Fig. 8
- PROSPECT2 Data

**Notes**

- Reduce backgrounds: Li-capture and pulse-shape discrimination
- Signal, Main Backgrounds
- Inverse Beta Decay
- $\gamma$-like prompt, $n$-like delay
- Fast Neutron
- $n$-like prompt, $n$-like delay
- Accidentals
  - $\gamma$-like prompt, $\gamma$-like delay

**Equation**

$$PSD = \frac{Q_{\text{tail}}}{Q_{\text{full}}}$$
Demonstration: Energy Response

- Light yield remains high for Li-EJ309
  - 8200 photons/MeV (11500 for EJ309)
  - Sufficient for 4-5% full-cell resolution
  - Good PSD simultaneously attained
- Excellent uniformity along full cell
Demonstration: PSD

- PSD is maintained even at large cell sizes
  - Ability to reject many neutron-related, reactor gamma backgrounds
  - PSD highly uniform over entirety of meter-length cell
Demonstration: HFIR Backgrounds

- Sub-dominant change in trigger and ($\gamma$,n) rate with reactor status
  - Reduction of cosmogenic backgrounds are primary concern
  - Reactor-off periods will be very valuable
- Data-matched PROSPECT MC will provide full S:B estimate
  - Major cosmogenic reductions from topology, multiplicity expected in full cell
• Excellent oscillation discovery potential at PROSPECT
  
• If new sterile neutrino is where global fits suggest, it’s very likely we’ll see it with a year’s data

• No reliance on absolute spectral shape or normalization: pure relative L/E measurement

• Complimentary to current/future neutrino efforts (SBN $\nu_e$ app, SBN/MINOS+/IceCube $\nu_\mu$ dis)
Summary

- Additional data is necessary to resolve the Reactor Anomaly
- High-resolution SBL reactor measurements can significantly constrain the favored hypotheses
  - Relative spectral measurements at multiple baselines has sterile discovery potential with a single year of data
  - High-resolution absolute measurements provide new constraints on reactor antineutrino production
- PROSPECT has the experience, development, and infrastructure in place for the world’s pre-eminent SBL reactor effort.
  - Segmented LiLS design provides excellent resolution in position and energy
  - Have been characterizing HFIR site, prototypes for over a year at HFIR
PROSPECT Collaboration

10 universities
6 national laboratories

Updated whitepaper
arXiv:1309.7647

Website
http://prospect.yale.edu/

reactor sites

Brookhaven National Laboratory
Drexel University
Idaho National Laboratory
Illinois Institute of Technology
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee
Virginia Tech University
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University

INL
NIST
ORNL
Backup
Reactor Antineutrino Production

- Reactor $\bar{\nu}e$: produced in decay of product beta branches

- Each isotope: different branches, so different neutrino energies (slightly)

\[
S(E) = \sum_i F_i S_i(E) \quad F_i = \frac{W_{th} f_i}{\sum_k f_k E_k}
\]
Predicting $S_i(E)$, Neutrinos Per Fission

- Two main methods:
  - **Ab Initio** approach:
    - Calculate spectrum branch-by-branch using beta branch databases: endpoints, decay schemes
    - **Problem:** many rare beta branches with little information; infer these additions
  - Conversion approach
    - Measure beta spectra directly
    - Convert to $\bar{\nu}_e$ using ‘virtual beta branches’
    - **Problem:** ‘Virtual’ spectra not well-defined: what forbiddenness, charge, etc. should they have?

- Devised in 50’s, each method has lost and gained favor over the years

  King and Perkins, Phys. Rev. 113 (1958)
Predicting $S_i(E)$, Neutrinos Per Fission

- **Early 80s:** ILL $\bar{\nu}_e$ data fits newest *ab initio* spectra well
  
  Davis, Vogel, *et al.*, PRC 24 (1979)

- **1980s:** New reactor beta spectra: measurements — conversion now provides lower systematics
  

- **1990s:** Bugey measurements fit converted spectrum well
  

- **1980s-2000s:** Predicted, measured fluxes agree
High-Flux Isotope Reactor at ORNL

- Compact 85MW Core
- HEU: constant U-235 $\bar{\nu}_e$ spectrum
- 42% reactor up-time (5 yearly cycles)
- Available detector location at 6+ m
- Have surveyed reactor backgrounds

HFIR core viewed from above

HFIR core size and power distribution

HFIR gamma background survey

HFIR Reactor-on Gamma Survey
PROSPECT Location at HFIR

Wide door to grade level: bring detector subsystems in here

Moveable detector here…

Reactors behind here…

…then here

Detector mockup in true deployed position

HFIR Main Level Hallway

Have been working in this location for > 1 year; PROSPECT prototypes operating here since August 2014!
P20 Demonstration: Topology

- Examine charge, arrival time ratios between cell’s PMTs
  - Closer PMT to interaction will have more charge, shorter time

- Resolution along cell better than 10cm
  - More topology background rejection capability than we were expecting!

- Segmentation gives resolution in other two dimensions

P20 Reactor-Off Position Reconstruction

![Diagram of P20 Reactor-Off Position Reconstruction]

**PRELIMINARY**
P20 Demonstration: Sim/Data Agreement

• Have CRY- and Goldhagen-based cosmogenic neutron, muon sim

• Shows n-coincidences in good agreement with data

  • Provides confidence in modeling of full PROSPECT detector backgrounds

• Data-matched simulation will give predicted S:B for PROSPECT

P20 n-coincident triggers, data vs. MC

Simulation

Data

IBD-relevant region:
Good agreement!!!

P20 12-bit FADC saturation reduces energies in data

PRELIMINARY
What is the correct model?

- Have data points for conventional fuel ($^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$)
- HEU ($^{235}\text{U}$): independent constraint

Benefits of HFIR:

- 1 core versus many cores (Daya Bay, RENO)
- Easier model: only 1 isotope, no time-dependence

Implications for reactor monitoring:

- Example: what if 5MeV bump isn’t present for HEU fuel?
- In that case ‘bump’ size would be a proxy for $^{239}\text{Pu}$ concentration in core
Forbidden Decay Handling

- W-mediated weak interaction
- Use Fermi’s Golden rule to calculate

\[ N_\beta(W) = K p^2 (W - W_0)^2 F(Z, W) \]

From nuclear matrix element:
Extra factors of p pop in here for beta decays

- Hayes, et. al, PRL 112 (2014): conversion result highly dependent on forbidden-ness of virtual branches

- Capable of shifting predicted flux downward by 5%

- Has not been shown what forbidden decay treatment would reproduce both reactor beta and nuebar spectra — but it might be possible to do so

FIG. 3: Different treatments of the forbidden GT transitions contributing to the antineutrino spectrum summed over all actinides in the fission burn in mid-cycle of a typical reactor. The left panel shows the ratio of these antineutrino spectra relative to that using the assumptions of Ref. [4]. The right panel shows the spectra weighted by the detection cross section, where the additional curve in black uses the assumptions of Ref. [4]. The spectra are strongly distorted by the forbidden operators, being lower below the peak and in some cases more than 20% larger above the peak than Ref. [4]. The corresponding change in the number of detectable antineutrinos relative to [4] is -0.75%, 5.8% and 1.85% for the 0-, 1-, and 2- forbidden operators, respectively.
Ab Initio Disagreements

- 5 MeV ‘bump’ region produced by many isotopes of great concern to this decay heat measurement!
- Two anomalies from the same source?
- Reactor spectroscopy measurements can provide:
  - Direct check on existing TAGS measurements
    - TOTALLY different systematics!
  - NEW data if TAGS has not been done!
  - Isotopes: Rb-92, Sr-97, Cs-142

A. Sonsogni (BNL), (2010)
P20 Demonstration: Energy Response

- High, uniform, and stable light collection in full-length cell
  - Exact PE yield is likely to be different in full PROSPECT cells
- Good energy resolution visible
  - Existing P20 PE yield is high enough to achieve 4-5% energy resolution goal
- Many background peaks, calibration sources to choose from

PROSPECT20 Response to Bi-207

Muon MIP Peak in PROSPECT20
(Energy reduced from FADC saturation)

0.39 MeV
0.84 MeV

PRELIMINARY