Precision Reactor $\bar{\nu}_e$ Spectrum Measurements: Recent Results and PROSPECTs

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Bryce Littlejohn
Illinois Institute of Technology

Daya Bay Antineutrino Spectrum

PROSPECT Collaboration at HFIR
Outline

- Intro: Reactor $\bar{\nu}_e$ Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Future measurement of the $\bar{\nu}_e$ spectrum at PROSPECT
- Historical/current/future context for PROSPECT
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Reactor Neutrino History

• Reactor $\bar{\nu}_e$: a history of discovery
  Many experiments, differing baselines

1950s: First neutrino observation

1970s-80s-90s:
  Reactor flux,
  Cross-section measurements

1970s-80s-90s:
  Reactor flux,
  Cross-section measurements

2000s: $\bar{\nu}_e$ disappearance,
  $\nu_e$ oscillation measurements

2010s: $\theta_{13}$, precision oscillation measurements
Reactor Neutrino Discovery

• How are these discoveries made?
  • Comparing observed reactor neutrinos at different sites
  • Comparing observed reactor neutrinos to predictions based on some model of how nuclear reactors work

KamLAND, PRL 100 (2008)

Daya Bay, PRL 108 (2012)

2000s: $\bar{\nu}_e$ disappearance, $\bar{\nu}_e$ oscillation measurements

2010s: $\theta_{13}$, precision oscillation measurements
Reactor Antineutrino Production

- Beta branches produced when fission isotopes fission
  - Low-enriched (LEU): Many fission isotopes
  - Highly-enriched (HEU): U-235 fission only
- Overall fission rate described largely by reactor thermal power

LEU Fission Fragment Contributors

Vogel, et. al
Rev. Mod. Phys (2001)
Reactor Antineutrino Production

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

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

\[ F_i = \frac{W_{th} f_i}{\sum_k f_k E_k} \]
Reactor Antineutrino Detection

- Detect inverse beta decay with liquid or solid scintillator, PMTs
- IBD e+ is direct proxy for antineutrino energy

Example: Daya Bay Detector

Daya Bay Monte Carlo Data

Prompt $e^+$ spectrum

~30us capture time

Delayed n-cap spectrum

nH

nGd
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)

Example: Ce-144 Decay Scheme

Predicting $S_i(E)$, Neutrinos Per Fission

- **Early 80s:** ILL $\nu_e$ 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

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**Distance to reactor (m)**

Adapted From PRD 83 (2011)
Recent History: Problems Emerge

- **2010s:** Re-calculation of conversion for $\theta_{13}$ measurements
  - Start with ab initio approach
  - Subtract this from ILL beta spectra
  - Use conversion procedure on remaining beta spectrum: $\sim$10%
  - OR Huber: virtual branches only

- **Change in flux/spectrum!**
  - Flux increase from:
    - Conversion ($\sim$3%)
    - X-section (1%)
    - Non-equilibrium isotopes (1%)
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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.”
- “Yes: but probably attributable to uncertainties in the beta-to-\(\nu_e\) conversion.”
- “Yes: the deficit could result from short-baseline sterile neutrino oscillations.”
• 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.”
  
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We need more data!!
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

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?”

We need more data!!

Double Chooz, JHEP 10 (2014)

W. Zhong (Daya Bay) ICHEP 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”

• New \textit{ab initio} shape seems to match RENO/DC data quite well

• But not the flux…?

• Not enough data to constrain this situation further!


We need more data!!
• 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…

We need more data!!
Major implications for Standard Model if $\nu_s$ DO actually exist

Even if they do not, ability to constrain reactor $\bar{\nu}_e$ models

- Valuable for reactor oscillation experiments
- Inputs to reactor modeling
- ‘Reactor spectroscopy:’ probe individual branches in reactor spectrum
- Implications for non-proliferation

Spectrum of $\nu_e$ at $L \sim 53$km

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Precise Reactor Spectrum Measurements

- A lot yet to be learned from/about reactor $\bar{\nu}_e$ spectra
- In particular we could really use:
  - A high energy-resolution detector for precisely measuring absolute spectrum
  - A high position-resolution detector for comparing spectra between baselines
- Enter PROSPECT: the Precision Reactor Oscillation and SPECTrum Experiment
PROSPECT Collaboration

- 58 collaborators
- 11 universities
- 5 national laboratories

Reactor sites:
- Brookhaven National Laboratory (INL)
- University of Chicago
- Drexel University
- Idaho National Laboratory (INL)
- Illinois Institute of Technology
- Lawrence Livermore National Laboratory (ORNL)
- Le Moyne College
- National Institute of Standards and Technology (NIST)
- Oak Ridge National Laboratory (ORNL)
- Temple University
- University of Tennessee
- Virginia Tech University
- University of Waterloo
- University of Wisconsin
- College of William and Mary
- Yale University
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
• High Flux Isotope Reactor: ORNL
• Extensive passive shielding
• Segmented liquid scintillator target region: ~3 tons for near detector (Phase I)
• Moveable: 7-11 m baselines
PROSPECT Location at HFIR

Wide door to grade level: bring detector subsystems in here

Detector mockup in true deployed position

Gamma background survey detectors
IBD Detection in Target

- Inverse beta interactions in Li-loaded PSD 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

Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

Delay signal: ~0.5 MeV signal from neutron capture on $^6\text{Li}$
**Detector Target R&D**

- **Reflecting segment system**
  - Fabrication method identified
  - Testing differing materials

- **Li-loaded Scintillator**
  - Formulation methods identified
  - Numerous candidates produce desired scintillation light yield, timing

![Short Mockup Segment](image1)

![Specular Panel](image2)

**Liquid Scintillator Development**

- $^6\text{Li}$-doped LS with pulse shape discrimination (PSD) is key component of PROSPECT:
  - High and uniform neutron capture efficiency in compact detector
  - Particle ID capability for neutron capture and fast neutron recoils

- Commercial PSD LS + collaboration $^6\text{Li}$ chemistry

- Multiple approaches are making excellent progress:
  - Collaboration PSD LS + $^6\text{Li}$ chemistry
  - EJ-309 doped with BNL $^6\text{Li}$ chemistry
  - PSD enhanced LAB-LS doped with BNL $^6\text{Li}$ chemistry
  - Ultima-Gold doped with NIST $^6\text{Li}$ micro-emulsion
IBD Detector Response: Simulation

- Must reconstruct $e^+$ energy with high resolution and low bias
- Model response with lab-benchmarked simulations
  - Energy deposition outside LS
  - Normalization and linearity of light production, collection, etc. with energy
  - Light yield variations along cell
  - Variations between cells

PROSPECT detector simulations

Optics simulations, Relative cell response simulations underway
IBD Detector Response: Simulation

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PROSPECT detector simulations
IBD Detector Response: Simulation

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PROSPECT detector simulations

Collection Efficiency

Position Along Cell (cm)

'Reconstructed' Energy (MeV)
IBD Detector Response: Calibration

- Must reconstruct $e^+$ energy with high resolution and low bias
- Characterize detector response with calibration sources
  - Fiber-delivered light sources
  - Guide tube-delivered gamma, neutron sources
  - Background sources: muons, radioactive backgrounds, spallation products

End view

Rigid rods hold reflecting walls in place

Center hole in rod for fibers, guide tubes

3D-printed rod prototypes
**IBD Detection Backgrounds**

- Have a highly sensitive detector operating at the surface in the direct vicinity of an operating nuclear reactor
- Major design challenge: background reduction
- Aiming for S:B ratio of 1:1

**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

**Prompt signal:** 1-10 MeV positron from inverse beta decay (IBD)

**Delay signal:** ~0.5 MeV signal from neutron capture on $^6$Li
Background Surveys

### Neutron Rate/Spectrum

- **2” Stilbene Organic Crystal**
  - "REM Ball"
  - Moderated $^3$He tube measured absolute thermal neutron flux at all sites
- **FaNS-1 Capture-gated Neutron Spectrometer**
  - Plastic scint. & 3He tubes measured spectrum and absolute flux at HFIR

### γ-ray Rate/Spectrum

- **Moderate Resolution:**
  - Same NaI(Tl) detectors used at all sites to provide relative comparison
- **High Resolution:**
  - Different HPGe and LaBr spectrometers used to identify background sources

### Muon Rate/Distribution

- Muon telescope assembled from 3 plastic scint. panels gives flux and angular distribution
- Telescope was tilted to measure angular distribution
- Different panel combinations defined angular acceptance

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From T. Classen
### Neutron Rate/Spectrum

**FaNS-1 Capture-gated Neutron Spectrometer**

- Moderated $^3$He tube measured absolute thermal neutron flux at all sites.
- "REM Ball" Stilbene Organic Crystal Plastic scint & $^3$He tubes measured spectrum and absolute flux at HFIR.

**Relative fast neutron flux at all sites**

<table>
<thead>
<tr>
<th>Location</th>
<th>Rate 4 – 14.5 MeV (mHz)</th>
<th>Rate 10-14.5 MeV (mHz)</th>
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<tbody>
<tr>
<td>ATR Near</td>
<td>4.7 ± 0.3</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>HFIR Near</td>
<td>2.2 ± 0.2</td>
<td>0.3 ± 0.1</td>
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<tr>
<td>NIST Near</td>
<td>2.8 ± 0.2</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>ATR Far</td>
<td>1.8 ± 0.2</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>HFIR Far</td>
<td>3.5 ± 0.2</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>NIST Far</td>
<td>2.8 ± 0.2</td>
<td>0.8 ± 0.1</td>
</tr>
</tbody>
</table>

### Muon Rate/Distribution

**Muon telescope** assembled from 3 plastic scint. panels gives flux and angular distribution. Telescope was tilted to measure angular distribution.

**Fast Neutron Rates**

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**Gamma Spectra (NIST)**

**Paper on results in preparation**
Background Shielding

- Shielding package designed based on background surveys, available space constraints
- Local lead shielding wall
  - Addresses ‘hot’ gamma regions
- Shielding encompassing entire detector
  - Li-Poly, B-Poly (neutrons), Lead (gammas)
- Investigating benefits of a muon veto system
- Backgrounds and effects of shielding have been simulated.
Background Rejection, Signal Selection

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

![Graph showing pulse shapes and PSD parameter](image)

**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

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

Fisher et al. NIMA 646 (2011)
PROSPECT: Scaling Up

- Measure n bgks
- Run DAQ, Remote data-taking
- See LS PSD
- See n-Li + PSD
- Demonstrate shielded background rates
- Demonstrate full-cell PSD, light yield
- Deploy final design concepts
- Observe relative segment responses
- See antineutrinos?
- **Deployment complete/imminent**

**PROSPECT 0.1**
- Aug. 2014
- See antineutrinos?
- **Physics!**

**PROSPECT 2**
- Dec. 2014
- **PROSPECT 20**
- Jan. 2015
- **PROSPECT 200**
- **PROSPECT 2ton**

*Approximate mass kg*
• Measure energy spectrum separately in each segment

• Look for unexpected L/E distortion: oscillations

• Mass splitting wouldn’t match observed three-neutrino splittings: fourth (sterile) neutrino

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

One 3x1x1 m³ detector, 1m³ 20 MW HEU core, 4m closest distance

Unoscillated

Oscillated:
\[ \Delta m^2 = 1.8 \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.5 \]

30% Efficiency
15cm position resolution
10%/\text{sqrt(E)} Energy Resolution
**PROSPECT Physics: Oscillations**

- Excellent oscillation discovery potential at PROSPECT
  - If new sterile neutrino is where global fits suggest, it’s very likely we’ll see it!
  - No reliance on absolute spectral shape or normalization: pure relative measurement
  - Good coverage with a single detector and one/three calendar years of data-taking

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**Simulated PROSPECT data, binned in L/E; Stat err. only**

![Graph showing oscillated/unoscillated ratio with baseline/energy on the x-axis and oscillated/unoscillated ratio on the y-axis.](image)

**Inputs:**
- 3+1 Oscillations
- $\Delta m^2 = 2.0 \text{ eV}^2$
- $\sin^2 2\theta_{13} = 0.1$

**Detection Efficiency:** 30%

**1:1 Signal:Background**

**Accessibility:**
- 20cm/10% position/energy resolution

**Sensitivity, Minimal Absolute Energy Spectrum Information**
- PROSPECT@HFIR, Phase I, 1 calendar year, 95% CL
- PROSPECT@HFIR, Phase I, 3 calendar years, 95% CL
- Reactor Anomaly, 95% CL
- All $\nu$, Disappearance Exps, 95% CL
• **What is the correct model?**
  - Have data points for conventional fuel ($^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu}$)
  - What about HEU fuel ($^{235}\text{U}$ only)? Provides additional model constraint

• **Benefits of HFIR:**
  - 1 core versus many cores (Daya Bay, RENO)
  - Easier to model, isolate features in 1 isotope’s beta branches?

• **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!
PROSPECT Physics: Absolute Spectrum

• How much fine structure exists in reactor spectrum?
  • Ab initio calculations suggest significant fine structure from endpoints of prominent beta branches

• PROSPECT can provide highest-ever energy resolution on the spectrum
  • Goal resolution: 4-5%
  • Thus, best measurement of this fine structure
  • Provide constraints on yields, endpoints of various branches (reactor spectroscopy)?
  • Provide input for future high-resolution reactor experiments (JUNO)?

HEU, 4.5% Energy Resolution

HEU Fuel
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Historical Context

- A similar experimental setup in the past: Bugey-3
  - Segmented short-baseline LiLS detector

- PROSPECT Pros:
  - Smaller reactor core, closer to core: better for SBL oscillation search
  - Stable scintillator: Bugey’s degraded after a few months in near detector!
  - Smaller target dead volume: ~2% versus >15% for Bugey
  - Aim for better light yield, PSD

- PROSPECT Con: No Overburden
  - 14+ mwe (Bugey-3), <10 mwe (PROSPECT)
  - Bugey had 25:1 S:B
US Context

- **NuLat**: Another effort to measure SBL reactor neutrinos in US
- Based on LENS optical lattice concept
- 2.5” B-loaded solid scintillator cubes, stacked together into lattice
- Observed on all sides by 1350 PMTs
- Test at 20MW NIST reactor, Data deployment at reactor aboard US Navy Ship
- Design, simulation and sensitivity studies underway currently
- Also proposed: coherent scattering at reactors
Many experiments: Russian, European, Asian Efforts

Key physics considerations (besides stats)
- Oscillation: Baseline proximity, range, resolution
- Spectrum: Energy resolution

PROSPECT: Relatively unique in designing toward both goals

My (biased) overview of global efforts

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Looking to Future

- Eventual PROSPECT Goal: Near and far detector (Phase II)
  - 4-10x larger far detector installed after near detector running
  - Provides broad, highly sensitive oscillation search
  - Far detector can provide highly-fiducialized, high-resolution spectrum

HFIR, Near and Far detectors

Phase I and Phase II sensitivities

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Summary

• Much has been learned about the absolute reactor nuebar flux and spectrum in the past 2-3 years

• More data is needed to address persisting questions

• PROSPECT can provide valuable new data by measuring HEU reactor $\bar{\nu}_e$ at short baselines
  • High position resolution allows a precise relative spectral measurement for testing the sterile neutrino solution to the reactor anomaly
  • High energy resolution allows a precise absolute spectral measurement for providing new constraints on reactor models
  • Valuable conclusions can be drawn with 1 calendar year of data

• R&D and prototype deployments at HFIR are well underway
END