Reactor Neutrinos
Recent Results and Future PROSPECTs

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Reactor Antineutrinos

A Tool for Discovery

2012 - Measurement of $\theta_{13}$ with Reactor Neutrinos

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos

Daya Bay, Double Chooz RENO

Saevannah River

2012 - Measurement of $\theta_{13}$ with Reactor Neutrinos

KamLAND

Daya Bay,
Double Chooz
RENO

? a story of varying baselines...
Open Questions in Neutrino Physics

Discoveries of neutrino oscillation, mass, and mixing

Open Questions

- How do neutrinos oscillate?
- What is the ordering of the mass states?
- Are there more than 3 neutrinos?
- Other neutrino properties or new physics?
- Is there CP violation?
- Are neutrinos their own antiparticles?
- What is the absolute neutrino mass?

Reactor neutrinos may also inform nuclear reactor models …

Reactor neutrinos
Reactor Antineutrinos

\( \bar{\nu}_e \) from \( \beta \)-decays, pure \( \bar{\nu}_e \) source

of n-rich fission products

on average \( \sim 6 \) beta decays until stable

\( > 99.9\% \) of \( \bar{\nu}_e \) are produced by fissions in

\( ^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu} \)

mean energy of \( \bar{\nu}_e \): 3.6 MeV

only disappearance experiments possible

From Bemporad, Gratta and Vogel

observed spectrum

reactor spectrum

cross-section

\( E_\nu \) (MeV)

Arbitrary

Karsten Heeger, Yale University

Miami 2016, December 18, 2016
Reactor Neutrino Oscillation Experiments

Measure (non)-1/r² behavior

for 3 active ν, two different oscillation length scales: \( \Delta m^2_{12}, \Delta m^2_{23} \)

\( \Delta m^2_{23} = \sim 2.4 \times 10^{-3} \text{ eV}^2 \)

\( \Delta m^2_{12} = \sim 7.6 \times 10^{-5} \text{ eV}^2 \)

oscillation frequency \( L/E \rightarrow \Delta m^2 \)
Relative Measurement of $\bar{\nu}_e$ Flux and Spectrum

**Absolute Reactor Flux**
Largest uncertainty in previous measurements

**Relative Measurement**
Removes absolute uncertainties!

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \right)$$

relative measurement (largely) cancels reactor systematics
Daya Bay Reactor Experiment

6 detectors, Dec 2011- Jul 2012
now running with 8 detectors

target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: \((7.5 / \sqrt{E} + 0.9)\%\)

Gd-doped liquid scintillator

Daya Bay Reactor Experiment

Experimental Hall

Antineutrino Detector

mineral oil

Gd-doped liquid scintillator

liquid scintillator γ-catcher
Antineutrino Candidates (Inverse Beta Decay)

Inverse Beta Decay

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

**Prompt event:**
positron deposits energy and annihilates (~ns)

**Delayed event:**
neutron thermalizes and captures on Gd

Prompt + Delayed Coincidence
Daya Bay Antineutrino Rate & Spectrum

Daya Bay near hall

Ling Ao near hall

Far hall

Rate

Spectrum

1230 days
Observation of $\bar{\nu}_e$ Disappearance

Based on 55 days of data with 6 ADs, discovered disappearance of reactor $\bar{\nu}_e$ at short baseline. [PRL 108, 171803]

Obtained the most precise value of $\theta_{13}$:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$$  [CPC 37, 011001]

2012 - One of Science’s breakthroughs of year
2015 - Breakthrough Prize in Fundamental Physics
Neutrino oscillation is energy and baseline dependent

$$P_{i \rightarrow j} = \sin^2 2\theta \sin^2 \left(1.27\Delta m^2 \frac{L}{E}\right)$$

Daya Bay demonstrates L/E oscillation

arXiv:1610.04802

Daya Bay
Daya Bay Neutrino Oscillation

\[
\sin^2 2 \theta_{13} = 0.0841 \pm 0.0027 \text{(stat.)} \pm 0.0019 \text{(syst.)}
\]

\[
|\Delta m_{ee}^2| = [2.50 \pm 0.06 \text{(stat.)} \pm 0.06 \text{(syst.)}] \times 10^{-3} \text{ eV}^2
\]

\sin^2 2 \theta_{13} \text{ uncertainty: 3.9%}

\| \Delta m_{32}^2 \| \text{ uncertainty: 3.4%}

Consistent results with reactor and accelerator experiments

arXiv:1610.04802

Daya Bay
Global Comparison

\[ \sin^2 2\theta_{13} \text{ uncertainty: 3.9\%} \]
\[ |\Delta m^2_{32}| \text{ uncertainty: 3.4\%} \]

Consistent results with reactor and accelerator experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>0.0841 ± 0.0033</td>
</tr>
<tr>
<td>RENO</td>
<td>0.082 ± 0.010</td>
</tr>
<tr>
<td>D-CHOOZ</td>
<td>0.111 ± 0.018</td>
</tr>
<tr>
<td>T2K</td>
<td>0.161 ± 0.048</td>
</tr>
<tr>
<td>MINOS</td>
<td>0.186 ± 0.055</td>
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<tr>
<td>NH</td>
<td>0.051 ± 0.038</td>
</tr>
<tr>
<td>IH</td>
<td>0.093 ± 0.054</td>
</tr>
</tbody>
</table>

\[ |\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\text{eV}^2 \]
\[ \text{NH: } \Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}\text{eV}^2 \]
\[ \text{IH: } \Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3}\text{eV}^2 \]
Daya Bay Sensitivity Projections

Precision Measurements in $\sin^2 2\theta_{13}$ and $\Delta m^2_{ee}$

**$\sin^2 2\theta_{13}$**

**$\Delta m^2_{ee}$**

Major systematics:

$\theta_{13}$: Relative + absolute energy, and relative efficiencies

$|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds

Daya Bay expected to run through 2020. Aim to improve precision of $\sin^2 2\theta_{13}$ and $\Delta m^2_{ee}$ to < 3%
Reactor Neutrinos - 3ν Oscillations and Beyond

Is the 3-v picture complete?
Are there more than 3 neutrinos?

What is the mass hierarchy?

What is the absolute flux and spectrum of reactor antineutrinos?

Δm²_{new} ~ 1 eV²
Flux Deficit
Consistent with previous experiments

Spectral Deviation

Extra neutrino oscillations or artifact of flux predictions?

New feature in 4-6 MeV region of spectrum.

Understanding reactor flux and spectrum anomalies requires additional data

arXiv:1607.05378
Daya Bay
$\bar{\nu}_e$ Disappearance and Oscillation Searches

Reactor $\bar{\nu}_e$ measurements

$\bar{\nu}_e$ disappearance data

new oscillation signal requires:

$\Delta m^2 \sim O(1 \text{eV}^2)$ and $\sin^2 2\theta > 10^{-3}$

“sterile” neutrino states

Kopp et al, 1303.3011

$\Delta m^2_{\text{new}} \sim 1 \text{eV}^2$
Implications for Future Neutrino Program

Discovery of eV-scale sterile neutrinos would be a paradigm change for particle physics.

- Expected neutrino spectrum and sensitivity to CP violation for long-baseline neutrino program
- Effective neutrino mass measured by $0\nu\beta\beta$

Neutrinoless Double Beta Decay

Inverted Hierarchy

Normal Hierarchy

$\Delta m^2 = 15 \text{ meV}$

Gandhi, Kayser, Masud, Prakash arXiv: 1508.06275

K. Han
Sterile Neutrino Search: Daya Bay

\[ P_{ee} \approx 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

sterile neutrinos would appear as additional spectral distortion and overall rate deficit

No hint of light sterile neutrino

Most stringent limit for \( \Delta m_{41}^2 < 0.1 \text{ eV}^2 \)

Sterile Neutrino Search: Daya Bay+Minos+Bugey

Combined $\bar{\nu}_e$ disappearance of Daya Bay and Bugey with $\nu_\mu$ disappearance of MINOS

Excluded parameter space allowed by MiniBooNE & LSND for $\Delta m_{41}^2 < 0.8$ eV$^2$

Phys. Rev. Lett. 117 (2016) no.15, 151801
Reactor Antineutrinos

High-powered research reactors

HFIR, ORNL

highly-enriched (HEU):
mainly U-235, ~10-100 MW\textsubscript{th},

Commercial power reactors

Daya Bay

low-enriched (LEU):
many fission isotopes, ~GW\textsubscript{th}

“Point Source” vs Extended Core

HEU core provides static spectrum of $^{235}$U.
Precision Reactor and Oscillation Experiment

Physics Objectives
1. Search for short-baseline oscillation at distances <10m
2. Precision measurement of $^{235}$U reactor $\bar{\nu}_e$ spectrum

Experimental Approach
- reactor model-independent search for neutrino oscillations
- measurement of $^{235}$U spectrum with high energy resolution $<4.5\%/\sqrt{E}$ ($\sigma/E$)
- background rejection capabilities at near-surface through fiducialization
PROSPECT Physics

A Precision Oscillation Experiment

*Direct model-independent test of oscillation of eV-scale neutrinos*

Phase I = AD-I, 3 years
Phase II = AD-I + AD-II, 3+3 years

**Objectives**

- 4σ test of best fit after 1 year
- >3σ test of favored region after 3 years
- 5σ test of allowed region after 3+3 years

Daya Bay
PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement to address spectral unknowns

Objectives
Measurement of $^{235}$U spectrum
Compare different reactor models
Compare different reactor cores

Testing models of the $^{235}$U $\bar{\nu}_e$ energy spectrum

Improvement on ILL

Different reactor cores
Experimental Site

Access
Established on-site operation
User facility, easy 24/7 access
Exterior access at grade
Full utility access, incl. internet

Compact Core
- **Power:** 85 MW
- **Fuel:** HEU ($^{235}\text{U}$)
- **Core shape:** cylindrical
- **Size:** $h=0.5\text{m}$, $r=0.2\text{m}$
- **Duty-cycle:** 41%
Background Challenge

Surface Neutrino Detection

Must be close to research reactor

- Reactor-related backgrounds (gammas and thermal n)
- Detector will have to operate at the surface (or close to it)
- *Cosmic-rays are problematic*

Approaches to Background Mitigation:

- New detector design
- New liquid scintillator
- New shielding design
Detector Design
- $^6\text{Li}$ liquid scintillator
- minimum dead material
- double-ended PMT readout,
- light guides, 5” PMTs
- $\sim$5%/\sqrt{E}$ resolutions

Segmented Detector
relative measurement of L/E within detector

Relative Spectrum Measurement
search for relative shape distortions independent of reactor models/predictions
Antineutrino Event Identification with $^6$Li

**Inverse Beta Decay**

- **Signal**
  - inverse beta decay (IBD)
  - $\gamma$-like prompt, n-like delay

- **Backgrounds**
  - fast neutron
  - n-like prompt, n-like delay
  - accidental gamma
  - $\gamma$-like prompt, $\gamma$-like delay

**Background Reduction**

detector design & fiducialization

- IBD event in segmented $^6$LiLS detector

**Background Reduction**

- Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)
- Delay signal: ~0.5 MeV signal from neutron capture on $^6$Li

40$\mu$s delayed n capture

**Pulse Shape Discrimination**
Background Rejection via Segmentation

Segmentation

Cosmic neutron event

Representative 500 MeV primary

Fiducialization

Background Reduction Steps

• Efficient PSD and neutron tagging
• Identification of multiple particle interactions
• Fiducialization

Active suppression by >3 orders of magnitude
PROSPECT Detector and Shielding Development

**PROSPECT-0.1**
*Characterize LS*
Aug 2014-Spring 2015
5cm length
0.1 liters
LS, $^6$LiLS

**PROSPECT-2**
*Background studies*
Dec 2014 - Aug 2015
12.5 cm length
1.7 liters
$^6$LiLS

**PROSPECT-20**
*Segment characterization*
Scintillator studies
Background studies
Spring/Summer 2015
1m length
23 liters
LS, $^6$LiLS

**PROSPECT-50**
*Baseline design prototype*
Winter 2015
1x2 segments
1.2m length
50 liters
$^6$LiLS

*Technically ready to proceed to AD-1*

**PROSPECT AD-I**
*Physics measurement*
10x12 segments
1.2m length
~3 tons
$^6$LiLS

multi-layer shielding

PROSPECT Phase I AD-I
reactor core
Prototyping and Detector Assembly

- Ton-Scale Production (same as last)
- Self-production to ensure cleanness
- Purification applied
- Characterization and QA/QC
- Continuation for future large production (Far detector)
- Commercial production reactor available
- 10-L prototype deployed and tested
- 50-L baseline (expandable to 100-L)
- Easy to install and QA/QC instruments ready
PROSPECT Collaboration

4 national laboratories
10 universities
68 collaborators

Supported By

Karsten Heeger, Yale University

Miami 2016, December 18, 2016
Reactor neutrinos are a tool for discoveries.
- Reactors are flavor pure source of $\overline{\nu}_e$.
- 60 years after Reines and Cowan reactor $\overline{\nu}_e$ hold promise to reveal new physics.

Precision oscillation physics with Daya Bay
- firmly established neutrino oscillations over km-long baselines
- most precise measurement of $\sin^22\theta_{13}$ and $|\Delta m_{ee}^2|$, 1230 days of data
- stringent limit for neutrino mixing to light sterile neutrino for $|\Delta m_{41}^2| < 0.2 \text{ eV}^2$

New reactor measurements are required to address the rate and spectrum anomalies.

PROSPECT will resolve current anomalies
- probe favored region for eV-scale sterile neutrinos at $>3\sigma$ within 3 years
- measure the $^{235}\text{U} \overline{\nu}_e$ spectrum, complementary to LEU measurements
- proceeding with construction of Phase I detector
- data taking expected to commence in 2017

Thanks to Daya Bay and PROSPECT collaborations. After 60 years of reactor neutrino experiments, future is bright.