Neutrino Oscillations, Nuclear Safeguards, and Advanced Detector Development with Reactor Antineutrinos

Karsten Heeger
University of Wisconsin

BNL, March 29, 2013
Towards Precision Neutrino Physics

solar neutrino problem
1960-1990

oscillation searches
1990-2000

precision measurements
2000 - Present

Anomalous results have led to a field of precision oscillation physics
Neutrino Oscillation Measurements

Recent Observations

- atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ disappear most likely to $\nu_\tau$ \((SK, MINOS)\)
- accelerator $\nu_\mu$ and $\bar{\nu}_\mu$ disappear at $L\sim250, 700$ km \((K2K, T2K, MINOS)\)
- some accelerator $\nu_\mu$ appear as $\nu_\mu$ at $L\sim250, 700$ km \((T2K, MINOS)\)
- solar $\nu_e$ convert to $\nu_\mu/\nu_\tau$ \((\text{Cl, Ga, SK, SNO, Borexino})\)
- reactor $\bar{\nu}_e$ disappear at $L\sim200$ km \((\text{KamLAND})\)
- reactor $\nu_e$ disappear at $L\sim1$ km \((\text{DC, Daya Bay RENO})\)

Experiments have demonstrated vacuum oscillation $L/E$ pattern

$$P_{i \to i} = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$$
Neutrino Oscillation Measurements

Recent Observations

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- reactor $\bar{\nu}_e$ disappear at L~200 km (KamLAND)
- reactor $\nu_e$ disappear at L~1 km (DC, Daya Bay RENO)

Vacuum to matter transition (MSW conversion) in Sun has been observed
Neutrino Oscillation Measurements

Recent Observations

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- accelerator $\nu_\mu$ and $\bar{\nu}_\mu$ disappear at $L \sim 250, 700$ km (K2K, T2K, MINOS)
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- reactor $\nu_e$ disappear at $L \sim 1$ km (DC, Daya Bay RENO)

<table>
<thead>
<tr>
<th>Solar Experiments</th>
<th>Reactor LBL (KamLAND)</th>
<th>Reactor MBL (Daya-Bay, Reno, D-Chooz)</th>
<th>Atmospheric Experiments</th>
<th>Accelerator LBL $\nu_\mu$ Disapp (Minos)</th>
<th>Accelerator LBL $\nu_e$ App (Minos, T2K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\rightarrow \theta_{12}$</td>
<td>$\rightarrow \Delta m_{21}^2$</td>
<td>$\rightarrow \theta_{13}$</td>
<td>$\rightarrow \Delta m_{atm}^2$</td>
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<tr>
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<td>$\rightarrow \Delta m_{21}^2$</td>
<td>$\rightarrow \theta_{13}$</td>
<td>$\rightarrow \Delta m_{atm}^2$</td>
<td>$\rightarrow \delta_{cp}$</td>
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<td>$\rightarrow \Delta m_{atm}^2$</td>
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<td>$\rightarrow \theta_{13}$</td>
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<td></td>
<td></td>
<td>$\rightarrow \theta_{13}$</td>
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</tbody>
</table>

Gonzalez-Garcia et al, ICHEP2012

complete suite of measurements can over-constrain the 3-v framework
# Neutrino Oscillation - 2012

## 3-ν Global Analyses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>1σ range</th>
<th>2σ range</th>
<th>3σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m^2 / 10^{-5}$ eV$^2$ (NH or IH)</td>
<td>7.54</td>
<td>7.32 – 7.80</td>
<td>7.15 – 8.00</td>
<td>6.99 – 8.18</td>
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<tr>
<td>$\sin^2 \theta_{12} / 10^{-1}$ (NH or IH)</td>
<td>3.07</td>
<td>2.91 – 3.25</td>
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<td></td>
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<tr>
<td>$\Delta m^2 / 10^{-3}$ eV$^2$ (NH)</td>
<td>2.43</td>
<td>2.33 – 2.49</td>
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<tr>
<td>$\Delta m^2 / 10^{-3}$ eV$^2$ (IH)</td>
<td>2.42</td>
<td>2.31 – 2.49</td>
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<td></td>
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<tr>
<td>$\sin^2 \theta_{13} / 10^{-2}$ (NH)</td>
<td>2.41</td>
<td>2.16 – 2.66</td>
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<tr>
<td>$\sin^2 \theta_{13} / 10^{-2}$ (IH)</td>
<td>2.44</td>
<td>2.19 – 2.67</td>
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<td>$\sin^2 \theta_{23} / 10^{-1}$ (NH)</td>
<td>3.86</td>
<td>3.65 – 4.10</td>
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<td>$\sin^2 \theta_{23} / 10^{-1}$ (IH)</td>
<td>3.92</td>
<td>3.70 – 4.31</td>
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<tr>
<td>$\delta / \pi$ (NH)</td>
<td>1.08</td>
<td>0.77 – 1.36</td>
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<tr>
<td>$\delta / \pi$ (IH)</td>
<td>1.09</td>
<td>0.83 – 1.47</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ref: Fogli et al 1205.5254 and Nu2012
Measurement of Fundamental Parameters

Mass Splittings

KamLAND has measured $\Delta m_{12}^2$ to $\sim 2.8\%$
Reactor Neutrinos

2008 - Precision measurement of $\Delta m_{12}^2$. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

55 years of liquid scintillator detectors a story of varying baselines...

Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Reactor Antineutrinos

Source

\( \bar{\nu}_e \) from \( \beta \)-decays of n-rich fission products

pure \( \bar{\nu}_e \) source

> 99.9% of \( \bar{\nu}_e \) are produced by fissions in \( ^{235}\text{U} \), \( ^{238}\text{U} \), \( ^{239}\text{Pu} \), \( ^{241}\text{Pu} \)

Detection

inverse beta decay

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

observed spectrum

calculated reactor spectrum

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

only disappearance experiments possible

From Bemporad, Gratta and Vogel
Hanford Experiment

inverse beta decay
\( \bar{\nu}_e + p \rightarrow e^+ + n \)

300 liters of liquid scintillator loaded with cadmium

signal: delayed coincidence between positron and neutron capture on cadmium

0.41 +/- 0.20 events/minute

high background (S/N ~ 1/20) made the experiment inconclusive
The Savannah River Detector

A new design (1959)

tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

target tanks (blue) were filled with water+cadmium chloride

Shielding: 4 ft of soaked sawdust

shielding and background reduction is important
tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

first reactor $\bar{\nu}_e$ spectrum

Reines, Cowan, Phys Rev 113, (1959)273
Observation of Reactor $\bar{\nu}_e$ Disappearance

KamLAND 2003

55 reactors

mean, flux-weighted reactor distance

$\sim$ 180km
Direct Evidence for Neutrino Oscillations

Reactor $\bar{\nu}_e$ with KamLAND

Neutrino Oscillation Imply Neutrino Mass

$\nu$ mass eigenstates ≠ flavor eigenstates

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

flavor composition of neutrinos changes as they propagate

2-neutrino case

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

energy and baseline dependent
osc frequency depends on $\Delta m^2$
amplitude depends on $\theta$

Neutrino Oscillations are Physics Beyond the Standard Model
Measurement of the Neutrino Mixing Angle $\theta_{13}$

Data taking since 2011

First observation of electron antineutrino disappearance over km-long baselines

Science Magazine
Daya Bay one of the “Breakthroughs of the Year 2012” after Higgs discovery
Reactor Neutrino Oscillation Experiments

Measure (non)-1/r^2 behavior of $\bar{\nu}_e$ interaction rate

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

$\Delta m^2_{atm}$

$\Delta m^2_{sol}$

$L \sim 1-2 \text{ km}$

$L \sim 60 \text{ km}$

$L/E \rightarrow \Delta m^2$ amplitude of oscillation $\rightarrow \theta$
Reactor Neutrino Oscillation Experiments

Absolute Reactor Flux
Largest uncertainty in previous measurements

Relative Measurement
Removes absolute uncertainties!

\[ \frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right] \]

far/near $\bar{\nu}_e$ ratio target mass distances efficiency oscillation deficit

Baseline (km)

$\Delta m^2_{\text{atm}}$ $\Delta m^2_{\text{sol}}$

$\theta_{13}$ $\theta_{12}$

$L \sim 1-2 \text{ km}$ $L \sim 60 \text{ km}$
Completing the 3-v Oscillation Picture

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

3-flavor picture needed

atmospheric/beam neutrinos

\[ \theta_{23}, \Delta m_{23}^2 \]

solar/reactor neutrinos

\[ \theta_{12}, \Delta m_{12}^2 \]

http://hitoshi.berkeley.edu/neutrino
Neutrino Oscillation

Mixing Angles & Mass Splittings

\[
\begin{align*}
U_{MNSP} & \text{ Matrix} \\
Maki, Nakagawa, Sakata, Pontecorvo
\end{align*}
\]

\[
U = \begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

\[
|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle
\]

\[
\begin{align*}
\theta_{23} &= 40.4^{+0.8}_{-1.8}^\circ \\
\theta_{13} &= 8.7^{+0.45}_{-0.45}^\circ \\
\theta_{12} &= 32.4^{+0.8}_{-0.8}^\circ
\end{align*}
\]

maximal? not so small large, but not maximal!

All three neutrino mixing angles are now known!
Reactor Antineutrino Oscillations

Early experiments 1956-2000

Daya Bay (RENO, DC) 2012

KamLAND 2003

Distance to Reactor (m)

Distance to Reactor (m)

Baseline (km)

N_{\text{obs}}/N_{\text{exp}}

N_{\text{det}}

\Delta m^2_{\text{atm}}

\Delta m^2_{\text{sol}}

\theta_{13}

\theta_{12}

L \sim 1-2 \text{ km}

L \sim 60 \text{ km}
Towards a Precision Reactor Spectrum

Reines 1959

Goesgen 1986

Daya Bay (> 200,000 events at near site)
Neutrinos - Open Questions

The Origin of Mass
• Why are neutrinos so light?
• Do neutrinos have Majorana mass?
• What is the absolute mass scale?
• Normal or inverted mass ordering?
• Are there more than 3ν?

The Flavor Puzzle
• Why is lepton mixing so different from quarks?
• CP violation?
• θ_{23} octant?
Reactor Neutrinos Beyond Daya Bay

Normal or inverted mass ordering?

Short-baseline oscillations? Are there more than 3ν?
Neutrino Anomalies

Anomalies in 3-ν interpretation of global oscillation data

LSND (ν_e appearance)
MiniBoone (ν_e appearance)
Ga anomaly
Reactor anomaly (ν_e disappearance)

new oscillation signal requires $\Delta m^2 \sim O(1\,\text{eV}^2)$ and $\sin^22\theta > 10^{-3}$

systematics or experimental effect? $\Rightarrow$ need to test effects

Cosmology suggests higher radiation density $N_{\text{eff}} > 3$
Neutrino Anomalies - Beyond 3ν?

Reactor

Are $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ consistent?

strong tension if all three are combined, tension also in 3+2 fit, consistent interpretation difficult

future data at the eV$^2$ scale will help, as well as cosmology
Neutrino Anomalies - Beyond 3ν?

Oscillation Interpretation of $\nu_e$ disappearance

$\Delta m^2 \sim O(1\text{eV}^2)$

At ~1km reactor $\theta_{13}$ experiments probe overall suppression
Reactor $\bar{\nu}$ Fluxes

Theory Meets Experiment

Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated


Re-evaluations find higher fluxes by about 3.5%

Ref: Mention et al, 1101.2755 (2012 upd)

Missing nuclear physics or new physics?
Reactor $\bar{\nu}$ Fluxes

Theory Meets Experiment

Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated


Re-evaluations find higher fluxes by about 3.5%

Two issues:

1. Model-dependence of physics determining the increase in the spectra?
   - SM physics for GT and Fermi Transitions
   - some transitions are forbidden transitions, corrections unknown

2. Overall uncertainties in reactor antineutrino fluxes?

Ref: Mention et al, 1101.2755 (2012 upd)
Reactor Flux Measurements

The “Anomaly”

Perhaps no anomaly at all?

Ref: arXiv: 1303.0900
Reactor Fluxes, Spectra, and $\theta_{13}$ Experiments

What about the $\theta_{13}$ experiments?

Reactor $\theta_{13}$ can test flux predictions within theoretical uncertainties but not directly search for short-baseline oscillations.
Reactor Fluxes, Spectra, and $\theta_{13}$ Experiments

Compare Reactor Spectra and Fluxes to Predictions

**spectrum**

Daya Bay data

**absolute flux measurements**

<table>
<thead>
<tr>
<th>Source</th>
<th>Item</th>
<th>Abs Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>H/Gd n-Capture Ratio</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Delayed Energy</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Number of Protons</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Spill-in Effects</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Subtotal</td>
<td>1.8</td>
</tr>
<tr>
<td>Detector</td>
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<tr>
<td></td>
<td>Thermal power uncertainty</td>
<td>0.5</td>
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<tr>
<td></td>
<td>Fission fraction</td>
<td>0.6</td>
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<tr>
<td></td>
<td>Spent fuel contribution</td>
<td>0.3</td>
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<tr>
<td></td>
<td>Subtotal</td>
<td>0.8</td>
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<tr>
<td>Flux normalization</td>
<td>Theoretical prediction</td>
<td>2.7</td>
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<tr>
<td></td>
<td>Bugey-4 anchor</td>
<td></td>
</tr>
</tbody>
</table>

**will test predictions of spectrum and flux within uncertainties**

Ref: Daya Bay run plan
Disappearance Searches

Ref: arXiv: 1303.3011
$\nu_\mu \rightarrow \nu_\text{e}$ Appearance Searches

Ref: arXiv: 1303.3011
Global Analysis

appearance data vs exclusion limit

experiments with signal vs constraints from other data

Ref: arXiv: 1303.3011
Radiation density in universe typically parameterized by $N_{\text{eff}}$

Joint constraints on $N_{\text{eff}}$ and $\Sigma m_\nu$ are always model-dependent

For $N_{\text{eff}} < 3.046$, no extra species

$N_{\text{eff}} = 3.29^{+0.67}_{-0.64}$  \hspace{1cm} (95%; Planck+WP+highL).

$\sum m_\nu < 0.60 \text{eV}$ \hspace{1cm} (78)

These bounds tighten somewhat with the inclusion of BAO data, as illustrated in Fig. 28; we find

$N_{\text{eff}} = 3.32^{+0.54}_{-0.52}$  \hspace{1cm} (95%; Planck+WP+highL+BAO).

$\sum m_\nu < 0.28 \text{eV}$ \hspace{1cm} (79)

For $\Delta N_{\text{eff}} \neq 0$

$N_{\text{eff}} < 3.91$ \hspace{1cm} (95%; CMB for $m_{\text{thermal}}^{\text{sterile}} < 10 \text{eV}$).

$m_{\nu,\text{sterile}}^{\text{eff}} < 0.59 \text{eV}$ \hspace{1cm} (82)

Combining further with BAO these tighten to

$N_{\text{eff}} < 3.80$ \hspace{1cm} (95%; CMB+BAO for $m_{\text{thermal}}^{\text{sterile}} < 10 \text{eV}$).

$m_{\nu,\text{sterile}}^{\text{eff}} < 0.42 \text{eV}$ \hspace{1cm} (83)

bounds are only marginally compatible with a fully thermalized sterile neutrino ($N_{\text{eff}}=4$) with sub-eV mass $< 0.5 \text{eV}$ that could explain the oscillation anomalies.

Ref: Planck results 2013
Neutrinos and Cosmology

Radiation density in universe typically parameterized by $N_{\text{eff}}$

Joint constraints on $N_{\text{eff}}$ and $\Sigma m_\nu$ are always model-dependent

great progress in cosmology, but model-dependent

Ref: Planck results 2013
Sterile Neutrinos would require $\Delta m^2 \sim O(1\text{eV}^2)$

Reactor Antineutrinos

$\bar{\nu}_e$ Oscillation

$\Delta m^2 \sim 2 \text{eV}^2$

distance, $R$

$\sim O(10)\text{m}$

Energy and baseline dependent effect
Opportunity for US Reactor Experiment

High-Power US Research Reactors

NBSR, NIST
ATR
HFIR, ORNL

Shortest Accessible Baselines

available baselines at US research reactors

existing data
3 neutrino oscillation illustration
4 neutrino oscillation illustration

Karsten Heeger, Univ. of Wisconsin
BNL, March 29, 2013
A Short-Baseline Reactor Experiment

Reactor Power and Duty Cycle

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Power (MW&lt;sub&gt;th&lt;/sub&gt;)</th>
<th>Baselines (m)</th>
<th>Reactor On (Days)</th>
<th>Reactor Off (Days)</th>
<th>Down-Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST</td>
<td>20</td>
<td>4-13</td>
<td>42</td>
<td>10</td>
<td>~32%</td>
</tr>
<tr>
<td>HFIR</td>
<td>85</td>
<td>6-8</td>
<td>24</td>
<td>18</td>
<td>~50%</td>
</tr>
<tr>
<td>ATR</td>
<td>250 (licensed) 110 (operational)</td>
<td>7-8 (restricted) 12-20 (full access)</td>
<td>48-56</td>
<td>14-21</td>
<td>~27%</td>
</tr>
<tr>
<td>ILL</td>
<td>58</td>
<td>7-9</td>
<td>50</td>
<td>41</td>
<td>~45%</td>
</tr>
<tr>
<td>SONGS</td>
<td>3438</td>
<td>24</td>
<td>639</td>
<td>60</td>
<td>8.6%</td>
</tr>
</tbody>
</table>

arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH
A Short-Baseline Reactor Experiment

Reactor Core Size

$\bar{\nu}_e$ Oscillation

Pathlength Spread

at detector from core

$\Delta m^2 \sim 2 \text{ eV}^2$

distance, $R$

$\sim 10 \text{ m}$

small core preferred to avoid washing out oscillation effect

arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH
A Short-Baseline Reactor Experiment

Reactor Core Size  \( \bar{\nu}_e \) Oscillation  Pathlength Spread

\[ \Delta m^2 \sim 2 \text{ eV} \]

~10m

small core preferred to avoid washing out oscillation effect

arXiv:1212.2182, PRD in press
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A Short-Baseline Reactor Experiment

Reactor Cores

3D Core

Reactor-Detector Distance

Vertical core cross-section

Horizontal core cross-section

relative event probability (AU)
neutrino path length (m)

Avg. Neutrino Path Length Spread (m)

Distance From Core Center (m)

arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH

Karsten Heeger, Univ. of Wisconsin  BNL, March 29, 2013
A Short-Baseline Reactor Experiment

Burnup of Reactor Fuel

> 99.9% of detected $\overline{\nu}_e$ are produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

<table>
<thead>
<tr>
<th>Fuel Isotope</th>
<th>Time-Averaged Fission Fraction</th>
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</thead>
<tbody>
<tr>
<td>Conventional Fuel</td>
<td>HEU fuel</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.59</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>0.29</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>0.05</td>
</tr>
</tbody>
</table>

HEU vs LEU Reactor Cores

HEU is a “static” core

arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH
A Short-Baseline Reactor Experiment

Reactor-Detector Distance: How close do we need to be?

Detector samples different oscillations for different $\Delta m^2$ $\rightarrow$ multiple detectors useful

Available baselines at US research reactors

Pointlike detector at closest distance to reactor
A Short-Baseline Reactor Experiment

Backgrounds

significant challenge, critical to know/measure background distributions

Background studies in progress at NIST

Ge detector

muon counter

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A Short-Baseline Reactor Experiment

Detector Resolution

Fractional Change in \( L/E \) Oscillation Amplitude

- Energy Resolution (%/\( \sqrt{E} \))
  - 5.0 eV\(^2\)
  - 1.8 eV\(^2\)
  - 0.15 eV\(^2\)

- Position Resolution (m)
  - nominal

\[ \Delta m^2 \ [	ext{eV}^2] \]

- 3 m Length, E+P, 3\( \sigma \) CL
- 1 m Length, E+P, 3\( \sigma \) CL
- 1 m Length, E-only, 3\( \sigma \) CL
- Reactor Anomaly, 95% CL
- Reactor Anomaly, 90% CL
- Global 3+1 Fit, 95% CL

arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH
A Short-Baseline Reactor Experiment

Experimental Parameters

detailed experimental design site specific

arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH
New Short Baseline Reactor Experiments

NEUTRINO-4 experiment

Preparation at WWR-M reactor (18 MW) in PNPI (Gatchina)

Reactor power - 18 MW
Size of active core - 0.6 m
reactor on without shielding
reactor off without shielding
reactor on/off with shielding

test of shielding

Installation of 2 sections test antineutrino detector with liquid scintillator (total volume 0.4 m³)

Installation of anticoincidence shielding from plastic scintillator 0.5x0.5x0.125 m³ with PMT (32 pieces)

A. Serebrov, PNPI
New Short Baseline Reactor Experiments

STEREO at ILL

Reactor Site
50 MW compact core ($\phi=40\text{cm}, h=80\text{ cm}$)

Short baseline [7-9] m

Pure $^{235}\text{U}$ spectrum

Background Rejection
Large passive and active shielding
15 m.w.e. overburden

Pulse Shape Discrimination

Segmented detector

On-site measurements in progress

Aim for first data in 2015
Funding decision in 2013

Shape analysis + 3.5 % uncertainty on normalization

Ref: Lhuillier
NUCIFER at Osiris

- Core: $\sigma \sim 0.3\text{m}$
- Baseline: 7m

- Norm error = 4%
- 100 days full power @ Osiris
- $S/B = 1$ (?), assuming same shapes (worst case).
- $E$ resol = 0.15$E$

Pre-industrial, unattended reactor neutrino monitor
May be used to test reactor anomaly with compact core. PSD R&D for background rejection.
SONGS Reactor Monitoring Experiment

SONGS - San Onofre Nuclear Power Generating Station

- High Flux: $\sim 10^{17} \text{ n/m}^2/\text{s}$
- 130-180m to other reactor
- Gallery is annular – unfortunately no possibility to vary baseline

Fuel diversion sensitivity determined by effect on burnup slope, possibility of power changes

SONGS1 detector (0.64t GdLS) deployed 24m from PWR, with $\sim 25\text{ mwe}$ overburden

Provided verification of operational history, fuel loading through burnup

Signal rate depends on power and fuel composition
SONGS Reactor Monitoring Experiment

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IAEA and Nuclear Non-Proliferation

• IAEA Interest:
  – Improved knowledge of input plutonium mass at reprocessing facility or repository – currently no better than 5-10%
  – Research reactor power monitoring – currently uses intrusive tech.
  – Verification of bilateral agreements – maybe future role for agency
  – Detection with minimal overburden – allows widespread deployment
Operation with Minimal Overburden and in High Backgrounds

**CORMORAD:** Gd/Plastic segments, no shield/veto

**PANDA36:** Gd/Plastic segments, no shield/veto

**Nucifer:** GdLS, lead/poly/veto, 7m from RR

**Rnd. Bkg** x10^2 Rx On/Off

**LLNL/SNL:** Gd-Water Cerenkov, poly shield/veto

**SNL/LLNL:** LiZnS/Plastic, poly shield/veto

Exp. signal/Obs. bkg \(\sim 1/100\)

Neutron capture PSD gives \(>10^2\) bkg rejection

Careful assessment of cosmogenic and reactor background required

Detectors with high selectivity of e+ and/or neutron capture required

Ref: Bowden, LLNL

Karsten Heeger, Univ. of Wisconsin

BNL, March 29, 2013
**Scintillator R&D Interests**

Develop organic crystals, liquids and plastics with good PSD and $^6\text{Li}$ loading

**Status**

- Good PSD obtained in plastic – now available commercially (undoped)
- Incorporated $^6\text{Li}$, $^{10}\text{B}$ in plastic and liquid
- $^6\text{Li}$ plastic not quite ready for large scale production
- Long term stability of $^6\text{Li}$ liquid not yet tested

Ref: Bowden, LLNL
Reactor Monitoring and Neutrino Oscillations

Reactor Monitoring

- Enable monitoring in different locations
- Enable tighter fissile material limits

Minimal overburden operation

- Operation in high n/γ fields
- High flash-point scint.

Efficient, compact, high res. detectors

Improved flux/spectrum knowledge

Short-baseline neutrino oscillation

- Oscillation experiment close to compact research reactor core
- 235U spectrum measurement

Ref: Bowden, LLNL
A Reactor Experiment at NIST?

Possible Detector Locations

Baselines
3.8m, 6.8m, 11.8, 15.2m (up to 25m?)
A Reactor Experiment at NIST?

Possible Detector Locations

![Detector Locations Diagram]

- **4-14m**

**Graph:**
- $\Delta m^2_{14} [eV^2]$ vs. $\sin^2 2\theta_{ee}$
- Curves labeled:
  - 1a, 1 year, 3σ CL
  - 1a + 1b, 1 year, 3σ CL
  - 1a + 2b (4x), 1 year, 3σ CL
  - 1a + 2b (10x), 1 year, 3σ CL
  - Reactor Anomaly, 95% CL
  - Reactor Anomaly, 90% CL
  - Global 3+1 Fit, 95% CL

Karsten Heeger, Univ. of Wisconsin  BNL, March 29, 2013
A Reactor Experiment at NIST?

Single vs Multi-Detector Experiment

2 detectors significantly increase the sensitivity of experiment, optimization in progress

Karsten Heeger, Univ. of Wisconsin

BNL, March 29, 2013
A Reactor Experiment at NIST?

Detector Module

detector modules are movable
low-utility use

Bugey

Fig. 1. A schematic view of one detection module and of the detection principle.
What are the expected improvements over Bugey-3?

- **smaller core size**
  - Bugey ran at a PWR, and to make matters worse, the shortest baselines were almost below it, looking along the long axis of that core

- **shorter baseline**
  - at US research reactors can get as close as 4m (Bugey > 15 m)

- **better scintillator stability**
  - some of the Bugey modules/detectors deteriorated
  - demonstrated stability of Gd-LS at Daya Bay for several years. Daya Bay scintillator produced by BNL

- **possibly better pulse shape discrimination (PSD)**
US Short-Baseline Reactor Experiment

**Objectives:**
- short-baseline sterile neutrino oscillation search
- precision measurement of reactor $\overline{\nu}_e$ spectrum for physics and safeguards
- develop antineutrino-based reactor monitoring technology for safeguards

**2-detector oscillation experiment**

**discovery potential**

![Diagram of reactor core with detectors 1 and 2, with distances labeled as ~4m and ~15m. Reactors under consideration: NIST, ATR, HFIR.](image)

**current R&D:**
- novel $^6$Li scintillator
- segmented detector and shielding design
- background measurements in progress
- background rejection and pulse shape analysis

**FY13-14** - R&D
**FY14-15** - design&construction
**FY 2016** - first data? (technically limited schedule)
US Short-Baseline Reactor Experiment

**Objectives:**
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- precision measurement of reactor $\bar{\nu}_e$ spectrum for physics and safeguards
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**Current Constraints**

**Discovery Potential**

- FY13-14 - R&D
- FY14-15 - design & construction
- FY 2016 - first data? (technically limited schedule)
**Scientific Opportunities for a US Reactor Experiment**

**Searches for new physics**
- probe **short-baseline oscillations** and test **sterile ν hypothesis**

**Reactor cores, fuel, and antineutrino spectra**
- precision measurement of **HEU reactor antineutrino spectrum**
- studying **HEU to LEU core conversion** at US research reactors

**Detector development**
- demonstrate operation of **on-surface antineutrino detectors**
- synergies with **safeguard** and reactor monitoring
- develop **scintillators for neutron detection** with PSD (Gd and Li-doped, LAB vs water)

**US community interested in pure and applied reactor antineutrino studies**
US Interest Group in Reactor Antineutrino Studies

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A Rich History of Reactor Neutrino Physics

Precision Studies with Reactor Antineutrinos

Antineutrino Discovery

Reactor $\bar{\nu}_e$ Spectra

neutrino magnetic moment and coherent scattering searches

$\bar{\nu}_e$ Oscillations

And more is yet to come...