20kt LS (undoped)
Acrylic tank: Φ34.5m
Stainless Steel tank: Φ37.5m
Reactor Neutrino – 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

Past Reactor Experiments
- Hanford
- Savannah River
- ILL, France
- Bugey, France
- Rovno, Russia
- Goesgen, Switzerland
- Krasnoyark, Russia
- Palo Verde
- Chooz, France
“El Monstro” – First design to detect (anti) neutrinos

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

20 kiloton bomb

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

“several times in a several-ton detector”

Reines and Cowan
Neutrino Discovery by Reines and Cowan in 1956

- Reactor anti-$\nu_e$ $\rightarrow$ Inverse beta decay + neutron capture

Hanford, WA, 1953, 300 L

Savannah River, SC, 1956, ~5000 L

At the time Cowan and I got into the act, a “big” detector was only a liter or so in volume – Reines, 1995
Reactor antineutrino

**Source**

Pure $\overline{\nu}_e$ from $\beta$-decays of n-rich fission products

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

**Detection**

inverse beta decay

$\overline{\nu}_e + p \rightarrow e^+ + n$

Threshold: neutrinos with $E < 1.8$ MeV are not detected

Disappearance experiments
Neutrino Oscillation -- two flavor scenario

\[ |\nu_e(t)\rangle = e^{-iE_1t}\cos \theta_0 |\nu_1\rangle + e^{-iE_2t}\sin \theta_0 |\nu_2\rangle \]

\[ L \text{ or } t \]

Survival Probability:

\[ P_{\nu_e \rightarrow \nu_e}(t) = 1 - \sin^2 2\theta_0 \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

- Energy and baseline dependent
- Oscillation frequency depends on \( \Delta m^2 \)
- Amplitude depends on \( \theta \)
1 kton liquid scintillator detector to measure reactor anti-$\nu_e$ disappearance.

Confirmed the deficits expected from $\nu$ oscillation

Observed the periodic feature of the anti-$\nu_e$ survival probability

mean, flux-weighted reactor distance $\sim 180$km
• 1 kton liquid scintillator detector to measure reactor anti-$\nu_e$ disappearance.
• Confirmed the deficits expected from $\nu$ oscillation
• Observed the periodic feature of the anti-$\nu_e$ survival probability

mean, flux-weighted reactor distance $\sim$ 180km
Neutrino mixing – 3 flavor

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{-i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Solar KamLAND

Short Baseline Reactor LBL Accelerator

Atmospheric LBL Accelerator

\[ c_{ij} = \cos(ij), \quad s_{ij} = \sin(ij) \]

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

\[ \Delta m_{23}^2 = \approx 2.4 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{12}^2 = \approx 7.6 \times 10^{-5} \text{ eV}^2 \]

amplitude of oscillation \( \theta \)

oscillation frequency \( L/E \to \Delta m^2 \)

Miami 2014

Ke Han, Yale University
Measuring $\theta_{13}$ with Reactor Experiments

Absolute Reactor Flux
Largest uncertainty in previous measurements

Relative Measurement
Removes absolute uncertainties!

First proposed by L. A. Mikaelyan and V. V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

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

far/near $\bar{\nu}_e$ ratio  target mass  distances  efficiency  oscillation deficit
Daya Bay – Observation of anti-$\nu_e$ Disappearance

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

\[
\sin^2 2\theta_{13} > 0
\]

Obtained the most precise value of $\theta_{13}$:
\[
\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005 \quad [CPC 37, 011001]
\]

- 6 “functionally identical” detectors
- Near Vs. Far
- multiple detectors allow comparison and cross-checks
A Precision Measurement of $\theta_{13}$

Best Fit + 68% C.L.

**Accelerator Experiments**
- Normal Hierarchy
- Inverted Hierarchy

*All results assuming:
$\delta_{CP} = 0$,
$\theta_{23} = 45^\circ$

**Reactor Experiments**
- Rate only
- Rate + Spectral
- n-Gd
- n-H

- **2011**
  - Solar+KamLand [1106.6028]
  - MINOS [1108.0015]
  - T2K 6 Events [1106.2822]
  - DC 101 Days [1112.6353]
  - Daya Bay 55 Days [1203.1669]
  - RENO 229 Days [1204.0626]
  - T2K 11 Events [ICHEP2012]
  - DC 228 Days [1207.6632]
  - Daya Bay 139 Days [1210.6327]
  - DC n-H Analysis [1301.2948]

- **2012**
  - RENO 416 Days [NuTel2013]
  - T2K 11 Events [1304.0841]
  - DC RRM Analysis [1305.2734]
  - T2K 28 Events [EPS2013]

- **2013**
  - Daya Bay 217 Days [NuFact2013]

$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$
Is the 3-ν picture complete? Sterile ν with eV scale mass?
What is the flux of reactor ν precisely? How about spectral shape?
What is the the ν mass hierarchy?
Precision measurement of oscillation parameters.
Oscillation parameter precision measurement

Proposed Projects: JUNO and RENO-50

RENO-50

JUNO

~60 km baseline

Precision 3-v Oscillation Physics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{12}$</td>
<td>3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\Delta m^2_{23}$</td>
<td>5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>6%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>20%</td>
<td>N/A</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>10%</td>
<td>15%</td>
</tr>
<tr>
<td>(~4% in 3 yrs)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mass Hierarchy

JUNO

*Current Site*

• JUNO

• Taishan

• Yangjiang

20 kt LS

Acrylic tank: d=34.5m
Stainless Steel tank: d=37.5m

\[ m_1^2 \]

\[ m_2^2 \]

\[ m_3^2 \]

\[ \nu_e \]

\[ \nu_\mu \]

\[ \nu_\tau \]

\[ m^2 \]

Normal

Inverted

\[ m_1^2 \]

\[ m_2^2 \]

\[ m_3^2 \]

atmospheric

\[ \sim 2.5 \times 10^{-3} \text{eV}^2 \]

solar

\[ \sim 7.6 \times 10^{-5} \text{eV}^2 \]

Mass Hierarchy Sensitivity

Ideal Spectrum 100 kTyear

\[ NH: |\Delta m^2_{32}| = 2.43 \times 10^{-3} \text{eV}^2 \]

\[ IH: |\Delta m^2_{32}| = 2.55 \times 10^{-3} \text{eV}^2 \]

\[ 10^{-3} \]

\[ 0.3 \]

\[ 0.2 \]

\[ 0.1 \]

\[ 2 \]

\[ 3 \]

\[ 4 \]

\[ 5 \]

\[ 6 \]

\[ E_\nu \ (\text{MeV}) \]

\[ \sigma \]

\[ 0 \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ 4 \]

\[ 5 \]

\[ 6 \]

\[ \text{Running time (yrs)} \]

JUNO

Ke Han, Yale University
• Reactor antineutrino anomaly: deficit in the observed reactor flux

Among other hints of sterile neutrino(s):
  – LSND
  – MiniBoone
  – Gallium
  – \(N_{\text{eff}}\) in cosmology

new oscillation signal requires \(\Delta m^2 \sim O(1\text{eV}^2)\) and \(\sin^2 2\theta > 10^{-3}\)
• Spectral deviation of data vs. prediction in 4-6 MeV

\[ \chi^2 = 41.4/24 \]
\[ p\text{-value} = 0.015 \]

Daya Bay

\[ 1.25 \text{ MeV} - 7 \text{ MeV} \]

• Recent ab-initio calculation provides a possible explanation involving decays from prominent fission daughter isotopes. Dwyer, Langford: arXiv:1407.1281
Vey short baseline reactor neutrino programs world-wide

STEREO: Gd-LS detector @10m from ILL, France

DANSS: Segmented plastic scintillator at ~10m from KNPP, Russia

Neutrino-4: Gd-LS detector @6-12m from SM-3, Russia

NuLAT/MTC: Boron-loaded plastic scintillator cubes on a nuclear submarine

SoLid: segmented composite scintillator cubes @ 5.5 m from BR2, Belgium

SBL@Korea: Gd-LS detector at ~30m from Hanbit
Two segmented Li-doped liquid scintillator detectors close to compact research reactor core:

- **Phase 1**: Near detector $O(2\text{ton})$
  - Precision spectrum measurement
  - Oscillation search
- **Phase 2**: Near + Far detector $O(10\text{ton})$
  - Enhanced oscillation search
- **Reactor Safeguards**:
  - Detection technology for operation near-surface and proximate to research reactor

Site characterization, detector R&D and prototype deployments are well underway
Core shapes

Advantages

- Compact HEU core
- Frequent outages for background measurement
- Multiple accessible baselines
- Detailed core models

<table>
<thead>
<tr>
<th>Site</th>
<th>Power</th>
<th>Duty Cycle</th>
<th>Near Baseline</th>
<th>Average Near Flux</th>
<th>Far Baseline</th>
<th>Average Far Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST</td>
<td>20 MW_{th}</td>
<td>68%</td>
<td>5.3m</td>
<td>1</td>
<td>17.0m</td>
<td>1</td>
</tr>
<tr>
<td>HFIR</td>
<td>85 MW_{th}</td>
<td>41%</td>
<td>7.9m</td>
<td>1.1</td>
<td>17.9m</td>
<td>2.3</td>
</tr>
<tr>
<td>ATR</td>
<td>110 MW_{th}</td>
<td>68%</td>
<td>10.1m</td>
<td>1.5</td>
<td>18.8m</td>
<td>4.5</td>
</tr>
</tbody>
</table>
2.5 ton active target at < 8 m baseline
(140 segments, 280 channels)

Single liquid tank containing full cell assemblies

Movable (airpads) to cover larger baseline (+1.5 m)
Extends sensitivity to lower $\Delta m_{14}^2$
Provides systematic checks
Detector Development– Segmentation Concept

- 2D segmentation provides 3D position resolution, reasonable channel count, and space efficiency
- Need for minimal dead material guides design
  - Goal: < 2% dead material (>15% for Bugey3)
- “Unit cell” built from reflecting separators and longitudinal posts – allows excellent calibration access
- Sealed PMT modules couple via acrylic light guides
Detector Development – Separators and LS

- Reflecting segment system
  - Fabrication method identified
  - Testing multiple material options

- Li-loaded Scintillator:
  - Formulation methods identified
  - Several candidates with good scintillation light yield, capture timing, PSD, compatibility

Short Mockup Segment  Specular Panel
• $^6$Li-capture and Pulse Shape Discrimination
• Strong rejection of accidental and correlated neutron backgrounds
• Using simulation/deployment data to understand and mitigate electromagnetic-neutron capture correlated backgrounds
PROSPECT progression

- Measure n, γ bkgds
- Run DAQ, Remote data-taking
- Examine n-Li + PSD, validate background simulation
- Demonstrate shielded background rates
- Demonstrate full-cell PSD, light yield
- Deploy final design concepts
- Study relative segment responses
- Aim for antineutrino detection

* Deployment complete/imminent

**PROSPECT 200**

**PROSPECT 20**
Dec. 2014
Jan. 2015

**PROSPECT 0.1**
Aug. 2014

**PROSPECT 2**
Dec. 2014

**PROSPECT 2ton**

Approximate mass kg
~2 liter Li-LS detector in small B-poly/ lead shield

- not representative of final shield design but useful for MC validation

Studies Underway:

• Muon correlations
• Detailed simulation comparison
• Internal background contribution (Rx off)
• …

10Hz Rx On singles rate > 200keV
-several orders of magnitude reduction with more to come

$^6$Li and fast neutron PSD strongly suppress backgrounds
Single component HEU core measurement will complement existing LEU spectrum measurements

- Additional model constraint from single, well modeled, reactor

Oscillation:

- Multiple segmented detectors probe wide L/E span, improving sensitivity over $\Delta m^2$ range of interest.
  - Phase I can rapidly provide significant physics potential
  - Phase II can address majority of suggested phase space
• Reactor neutrinos are a tool for discovery.
  – Reactors are flavor pure sources of anti-$\nu_e$ for FREE

• Current reactor experiments ($L \sim 1\text{-}2\text{km}$) provide precision data on $\theta_{13}$, and reactor antineutrino flux and spectra. Precision measurements will be input to long-baseline neutrino experiments.
  – Daya Bay, RENO, Double Chooz

• Medium-baseline experiments ($L \sim 60\text{km}$) may offer $<1\%$ precision oscillation physics and a window to the mass hierarchy.
  – JUNO, RENO-50

• Short-baseline ($L \sim 10\text{m}$) measurements offer opportunities for precision studies of reactor spectrum and a definitive search for short-baseline oscillation and sterile neutrinos.
  – PROSPECT, …