Review of Present and Future Reactor Neutrino Experiments

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Neutrino Oscillation Results

Missing information in 3x3 ν mixing scheme:

1. What is ν\textsubscript{e} component in the ν\textsubscript{3} mass eigenstate, i.e. θ\textsubscript{13} = ?
   - Only know θ\textsubscript{13} < ~11°.

2. Is the µ - τ mixing maximal?
   - Only know sin\textsuperscript{2}2θ\textsubscript{23} > 0.90.

3. What is the mass hierarchy?
   - Normal or inverted?

4. Do neutrinos exhibit CP violation, i.e. is δ\textsubscript{CP} ≠ 0?

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

\[ \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \sim \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta\textsubscript{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta\textsubscript{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \]

\[ \theta_{12} \sim 30° \]

\[ \sin^2 2\theta_{13} < 0.11 \text{ at 90% CL} \]

\[ \theta_{23} \sim 45° \]
Experimental Methods to Measure $\theta_{13}$

- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV$^2$
  - Look for appearance of $\nu_e$ in a pure $\nu_\mu$ beam vs. $L$ and $E$
- Use near detector to measure background $\nu_e$'s (beam and misid)

**NOvA:**
$\langle E_\nu \rangle = 2.3$ GeV  
$L = 810$ km

**T2K:**
$\langle E_\nu \rangle = 0.7$ GeV  
$L = 295$ km

- Reactors: Disappearance ($\overline{\nu}_e \rightarrow \overline{\nu}_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV$^2$
  - Look for a change in $\nu_e$ flux as a function of $L$ and $E$
  - Look for a non-$1/r^2$ behavior of the $\overline{\nu}_e$ rate
  - Use near detector to measure the un-oscillated flux

**Double Chooz:**
$\langle E_\nu \rangle = 3.5$ MeV  
$L = 1100$ m
Oscillation probability complicated and dependent not only on \( \theta_{13} \) but also:

1. CP violation parameter (\( \delta \))
2. Mass hierarchy (sign of \( \Delta m_{31}^2 \))
3. Size of \( \sin^2 \theta_{23} \)

\[
P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^{-2}
+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^{-2}
+ \cos \delta \sin 2\theta_{23} \sin 2\theta_{13} \cos \Delta_{32} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \frac{\sin(aL)}{(aL)} \Delta_{31} \Delta_{21}
+ \sin \delta \sin 2\theta_{23} \sin 2\theta_{13} \sin \Delta_{32} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \frac{\sin(aL)}{(aL)} \Delta_{31} \Delta_{21}
\]

\( \Rightarrow \) These extra dependencies are both a “curse” and a “blessing” since they will let us measure CP violation if \( \theta_{13} \) is big enough.
Accelerator vs Reactor Experiment

**Reactor Disappearance Experiments**

$\theta_{13}$ probed by measuring the disappearance of reactor produced electron anti-neutrinos.

- For $\theta_{13}$ need to work at an L/E matched to the atmospheric $\Delta m^2$.
- Reactors used in $\theta_{12}$ range as well: need to work at an L/E matched to the solar $\Delta m^2$ i.e. Kamland measurement at solar $\Delta m^2$.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2 \theta_{12} \sin^2 \Delta_{21}$$

$$- \sin^2 2 \theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

$$\Delta_{ij} \equiv 1.27 \Delta m^2_{ij} L / E$$

$L$(km), $E$(MeV), $m$(10$^{-3}$eV)

$$\Rightarrow$$ Reactor disappearance measurements provide a straight forward method to measure $\theta_{13}$ with no dependence on matter effects and CP violation.
Nuclear Reactors as $\bar{\nu}_e$ Sources

What creates the reactor $\bar{\nu}_e$’s?

- Typical modern nuclear power reactor has a thermal power of:
  \[ P_{\text{therm}} = 3.8 \text{ GW} \]
  - About 200 MeV / fission of energy is released in fission of $^{235}\text{U}$, $^{239}\text{Pu}$, $^{238}\text{U}$, and $^{241}\text{Pu}$.
  - The resulting fission rate, \( f \), is thus: \( f = 1.2 \times 10^{20} \) fissions/s
  - At 6$\bar{\nu}_e$ / fission the resulting yield is: \( 7.1 \times 10^{20} \bar{\nu}_e / s \).

Using $e^-$ spectra measurements for $^{235}\text{U}$, $^{239}\text{Pu}$, and $^{241}\text{Pu}$
Can calculate the $\nu_e$ flux to 2-3%.

Example: $^{235}\text{U}$ fission

\[
^{235}_{92}\text{U} + n \rightarrow X_1 + X_2 + 2n
\]

Most likely A from \( \Rightarrow ^{94}\text{Zr} ~ ^{140}\text{Ce} \)

$^{235}\text{U}$ fission

\( \rightarrow \) on average 6 n have to $\beta$-decay to 6 p to reach stable matter: \( ^{94}_{40}\text{Zr} ~ ^{140}_{58}\text{Ce} \)

\( \rightarrow \) on average 1.5 $\nu_e$ are emitted with energy $> 1.8$ MeV
**ν_e Flux Calculation**

- To perform this calculation correctly one must
  - consider 235U, 238U, 239Pu, and 241Pu (> 99.5% ν_e flux),
  - account for all possible β branches.
  - correct for evolution of the reactor core over the fuel cycle.

- Measurement of the β spectra of fissioning of U-235, Pu-239, and Pu-241 samples by thermal neutrons performed at ILL, and converted to neutrino spectra.

- U-238 relies on theoretical calculation, 10% uncertainty (P. Vogel et al., PRC24, 1543 (1981)). U-238 contributes (7-10)% fissions.

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**Graphs:**

Conversion from Electron to anti-Neutrino Spectra

- Old method (A. Schreckenbach et al.) used 30 effective β branches.

- Comparison of prediction to observation:

  Example:
  Goesgen Experiment
  Solid: Fit to Data
  Dashed: Prediction from β spectrum

  Another example Bugey 3 Exp: comparison to three different reactor spectrum models.

  Flux and Energy Spectrum known at ~2-3 % level
  → Reactors used as “calibrated sources” of ν’s

  Normalization error ~1.9%.
  Energy dependent (shape) error from 1.34% at 3 MeV to 9.2% at 8 MeV.
Reactor $\bar{\nu}$ Flux and “Reactor Anomaly”


Mueller et al. have refined method to go from measured $^{235}$U, $^{239}$Pu, and $^{241}$Pu $\beta^-$ spectra (at ILL) to neutrino spectra.

New method uses all available information on measured nuclei from nuclear databases (~90% info from data bases, remaining ~10% fitted with 5 effective branches)

The result is a +3% increase in neutrino flux, on average.

For $L<100\text{m}$, accounting for correlations, results is $\frac{N_{\text{OBS}}}{N_{\text{EXP}}} = 0.937\pm0.027$

Possible bias or new physics at short baselines? Results are compatible with 4th, sterile neutrino state with $\Delta m^2 \sim 1\text{eV}^2$ and $\sin^2 2\theta \sim 0.1$ (i.e. MiniBooNE/LSND, etc).
Detection Technique

- The reaction process is inverse $\beta$-decay followed by neutron capture
  - Two part coincidence signal is crucial for background reduction.
    \[ \bar{\nu}_e p \rightarrow e^+ + n \]
  - Positron energy spectrum implies the neutrino spectrum ($e^+e^-\rightarrow\gamma\gamma$)
    \[ E_\nu = E_{vis} + 1.8 \text{ MeV} - 2m_e \]
- The scintillator may be doped with gadolinium to enhance capture
  \[ n^m\text{Gd} \rightarrow n^{m+1}\text{Gd} \gamma \text{'s (8 MeV)} \]
- Cross accurate to 0.2%
  P. Vogel and J. Beacom,
  Phys.Rev.D60:053003,1999
  A. Strumia and F. Vissani,

Neutrinos with $E<1.8$ MeV are not detected.
Best Reactor $\theta_{13}$ Limit: CHOOZ Experiment

The current best limit for $\sin^2 2\theta_{13}$ is from the CHOOZ experiment: was built to find out if the atmospheric neutrino deficit was due to $\theta_{12}$, and the measurement of theta-13 was an unexpected by-product.

- One detector experiment
  - Major systematic was reactor flux
- Large singles rate due to radioactivity of PMTs
  - Problem was scintillator reaching out to tubes
- Detector stability issues with scintillator
  - Light output decreasing with $\tau = 720$ days
- Small fiducial mass:
  - CHOOZ: 5 tons @ 1km, 5.7 GW
  - ~2.2 events/day/ton with 0.2-0.4 bkgd events/day/ton
  - ~3600 $\nu$ events total

<table>
<thead>
<tr>
<th>parameter</th>
<th>relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>reaction cross section</td>
<td>1.9%</td>
</tr>
<tr>
<td>number of protons</td>
<td>0.8%</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>1.5%</td>
</tr>
<tr>
<td>reactor power</td>
<td>0.7%</td>
</tr>
<tr>
<td>energy released per fission</td>
<td>0.6%</td>
</tr>
<tr>
<td>combined</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

CHOOZ: $R_{\text{osc}} = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (syst)}$
$\sin^2 2\theta_{13} < 0.15$ for $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$

**MINOS:** For $\delta_{CP} = 0$, the allowed values $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ at 90% CL:
- Normal: 0 to 0.12, central value: 0.04
- Inverted: 0 to 0.19, central value: 0.08

**T2K:** For $\delta_{CP} = 0$, $\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV$^2$, $\sin^2 \theta_{23} = 1$, allowed values $\sin^2 2\theta_{13}$ at 90% CL
- Normal: 0.03 to 0.28, central value: 0.11
- Inverted: 0.04 to 0.34, central value: 0.14

See dedicated talks:
- MINOS by J. Nelson
- T2K by F. Di Lodovico
Non-zero $\theta_{13}$ Evidence

Recent global analysis fit for $\sin^2\theta_{13}$ vs $\sin^2\theta_{12}$: Fogli et al. arXiv: 1106.6028[hep-ph]

Is $\theta_{13}$ non-zero and within a reach? → Need new sensitive experiments to confirm!

$\sin^2 2\theta_{13} = \begin{cases} 0.021 \pm 0.007 , \text{ old reactor fluxes} \\ 0.025 \pm 0.007 , \text{ new reactor fluxes} \end{cases}$ (1σ)

$\sin^2\theta_{13} = 0.082 \pm 0.028 \quad 0.098 \pm 0.028$
How can one improve on CHOOZ Experiment and possibly measure $\theta_{13}$?

Add an identical near detector $\rightarrow$ eliminate dependence on reactor flux. Optimize baseline $\rightarrow$ near detector close to reactors, far detector at oscillation maximum.

Use larger detectors with reduced systematics uncertainties $\rightarrow$ improved statistics, minimize systematics.

High power reactor sites $\rightarrow$ improved statistics.

Reduce backgrounds $\rightarrow$ go deeper and use active veto systems.

Stable scintillator $\rightarrow$ eliminate aging effects.

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 (1.27\Delta m^2_{31}L / E_\nu) \]

Survival Probability

Oscillations observed as a deficit of $\nu_e$

Unoscillated flux observed here

$\sin^2 2\theta_{13}$
## New Multi-detector $\theta_{13}$ Reactor Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$GW_{th}$</th>
<th>Distance Near/Far (m)</th>
<th>Shielding Near/Far (mwe)</th>
<th>Target Mass (tons)</th>
<th>Sensitivity $\sin^22\theta_{13}$ (90% c.l.)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz (France)</td>
<td>8.4</td>
<td>390/1050</td>
<td>115/300</td>
<td>8/8</td>
<td>0.03</td>
<td>Data taking with far; near in 2012</td>
</tr>
<tr>
<td>RENO (Korea)</td>
<td>17.3</td>
<td>290/1380</td>
<td>120/450</td>
<td>16/16</td>
<td>0.02</td>
<td>Start mid-2011</td>
</tr>
<tr>
<td>Daya Bay (China)</td>
<td>17.4</td>
<td>360(500)/1985(1615)</td>
<td>260/910</td>
<td>$2\times2\times20$ (N) $4\times20$ (F)</td>
<td>0.01</td>
<td>Start mid-2012</td>
</tr>
</tbody>
</table>

- Many similarities in detector design and analysis strategy
- Differences in sensitivity come mainly from statistics (mass, reactor power), baseline optimization, and multiple detector sites (for Daya Bay)
Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea

Courtesy : S. B. Kim
Completed RENO Detector (Feb. 2011)

- DAQ Electronics
- Calibration System
- Gd-LS filling for Target
- LS filling for Gamma
- Water filling for Veto

Liquid(Gd-LS/LS/MO/Water) Production & Filling (May-July 2011)

- Both near and far detectors are filled with Gd-LS, LS & mineral oil as of July 5, 2011.
- Veto water filling is 90% through, and will be done in the end of July, 2011. Take data August 2011!
**RENO Sensitivity on \( \sin^2(2\theta_{13}) \)**

- **Statistical errors (3 years of data taking with 70% efficiency)**
  
  Near : \( 9.83 \times 10^5 \approx 10^6 \) (0.1% error)  
  Far : \( 8.74 \times 10^4 \approx 10^5 \) (0.3% error)

- **Systematic error** : \(<0.5\%\)

\* **Sensitivity** : \( \sin^2(2\theta_{13}) > 0.02 \) at 90% C.L.

![Graph showing sensitivity and limits](image)
The Daya Bay experiment at the Daya Bay nuclear power complex in Shenzhen, China.

Courtesy: K-B. Luk, Y. Wang
Also see the dedicated talk on “Status of Daya Bay” by Zhimin Wang
Daya Bay Experiment

- DYB Near 2x20t overbdn: 95m
- Far 4x20t overbdn 355m
- LA Near 2x20t overbdn 112m
- 1615m
- 1985m

Ling Ao (2011)

Daya Bay

Daya Bay/Ling Ao Power Plant
- 4 cores, 11.6 GWth
- 2011: 6 cores, 17.4 GWth

HONG KONG
8 identical, 3-zone detectors: 2@Near and 4@Far

target mass: 20t GdLS
detector mass: \(\sim 110\) t
photosensors: 192 PMTs

- Calibration system
- Top reflector
- Inner acrylic vessel (3m \(\varnothing H\))
- Outer acrylic vessel (4m \(\varnothing H\))
- Stainless steel vessel (5m \(\varnothing H\))
- Bottom reflector
Installation of ADs at Daya Bay Site and Schedule

- AD and muon veto systems are installed in Daya Bay Hall, dry run data taken.

- Begin data taking with two ADs in the Daya Bay Hall in the summer of 2011.

- Begin data taking with all eight ADs in three halls in 2012 to reach a design sensitivity of $\sin^2\theta_{13}$ of 0.01 or better.
Double Chooz Reactor Experiment in Ardennes, France
Chooz-B Power Plant
- 2 cores, 8.6 GWth

Near 8.6t overbdcn 45m

Far 8.6t overbdcn 110m
Improved Detector Design

Calibration glove box
Outer Veto: plastic scintillator strips
Shielding: steel 15 cm thick
Inner Veto: 90 m$^3$ of liquid scintillator
78 8” PMTs
Buffer: 110 m$^3$ of non-scintillating mineral oil
390 10” PMTs
Gamma-Catcher: 22.3 m$^3$ of liquid scintillator
Target: 10.3 m$^3$ of liquid scintillator doped with 1 g/L of Gd
Far Detector Installation
Stable Data Taking since April 13th 2011

- >70 full days of physics (Physics Run Eff. 75%)
- Trigger rate 120 Hz - Trigger threshold < 0.6 MeV
- Calibration runs 10% of the time (light injection through embedded fiber)
- Outer Muon Veto & Source Calibration systems being commissioned
Physics Data: Muons and Michel Electrons

- ~40Hz of muons tagged by Inner Veto.
- ~10Hz of muons tagged by Inner Detector.
- Delayed coincidence method works well and tags Michel electrons:
  selection Criteria based on time since stopped muon (µs) and energy requirements.
- Only Statistical errors shown here.

Muon Rate in the Inner Veto: 39 Hz

Michel electron timing distribution

Lifetime 2.25 ± 0.13 µs
Physics Data: Neutrons and Accidental Background Events

-Muon-correlated events in Gd-capture time window (left plot).
-Mostly spallation neutrons: Peaks of neutron capture on:
  Hydrogen (2.2MeV)
  Gadolinium (~8MeV).

-Caveat: un-calibrated data shown.

-Stability of the radioactivity background singles rate in the delayed energy window, i.e. under
gadolinium peak (right plot):
  muon-correlated events vetoed.
Calibration Systems

- Embedded LEDs inside inner detector and inner veto
  → routinely used to monitor detector stability and PMT gains.
- Calibration source ($\gamma$, n, $\beta$) deployment devices:
  - Z-axis system,
  - Guide tubes,
  - Articulated Arm.
- Radioactive sources ready for deployment (Cs-137, Co-60 Ge-68, Cf-252).
Current Status and Expected Sensitivity

- More than 70 full days of physics collected.
- Detector stable: singles rates, muon-rates, and neutron-capture rates are as expected.
- Correlated backgrounds being studied.
- Oscillation analysis under way.
- "Reactor Anomaly" and DC analysis with the far Detector only strategy: use the experimental cross section per fission of Bugey-4 (apply burn-up correction).
- T2K’s central values to be addressed at 99% CL with 2011 data.

For FD only phase, assume $\sigma_{\text{norm}} = 2.5\%$ and $\sigma_{\text{uncorr}} = 2\%$

Relation of T2K result and pure $\sin^2 2\theta_{13}$ (Double Chooz)
Double Chooz 90 and 99% CL Sensitivity
Double Chooz Near Detector Status

-Near Site/Lab Construction started 29th April 2011.

-Lab expected to be ready for physics April 2012.

-Near Detector ready at the end of 2012.
Expected Sensitivities of Current Short-baseline Experiments

What to do if $\theta_{13}$ very small/large? See dedicated talks: S. Garwalla, H. Minakata
Note on Sterile Neutrinos

• “The Reactor Antineutrino Anomaly,” G. Mention et al., Phys. Rev. D83, 073006, 2011: Results are compatible with 4th, sterile neutrino state with $\Delta m^2 >\sim 1 \text{eV}^2$ and $\sin^2 \theta \sim 0.1$.

• Oscillations driven by the extra sterile neutrinos would produce a constant suppression at both near and far detectors (picture complicated if $\Delta m^2<1\text{eV}^2$).

• Data from near and far detectors can be used to probe $\theta_{13}$ and $\theta_{14}$-driven effects.

See Dedicated Talks on Sterile vs: Bill Louis, C. Giunti
New Reactor Neutrino Experiments?

Atmospheric Range: New ideas might develop after current generation of experiments (Double Chooz, Daya Bay, RENO) is completed. -One of possible follow-up idea is “Triple Chooz” (P. Huber et. Al., arXiv: hep-ph/0601266).

Solar Range: An experiment with very large detector at oscillation maximum from powerful reactor complex would provide a very precise measurement of $\theta_{12}$ mixing; see for example H. Minakata et. Al., Phys.Rev. D71, 013005 (2005).

Sterile Neutrino Range: all current short-baseline experiments essentially sensitive -Near/far detector data from upcoming experiments should be studied closely. -A measurement of few MeV neutrinos at very short baseline (~10 m) would be interesting (note overlap with testing plutonium diversion at commercial reactor)  

SCRAAM: The Southern California Reactor Antineutrino Anomaly Monitor, USA Nucifer (France)  
DANSS (Detector of the Anti-Neutrinos based on the Solid Scintillator, Russia)  
...
Summary

• Exciting time for reactor $\bar{\nu}$ experiments: Upcoming experiments will tell us much about $\theta_{13}$ (hopefully measure it!).
• Measurement of $\sin^22\theta_{13} > 0.01$ is key to planning leptonic CPV searches in long-baseline $\nu$ oscillation experiments.
• New reactor flux calculation and “anomaly”:
  – Near/far detector experiment is the right way to measure $\theta_{13}$
  – Near detector data from upcoming experiments should be studied closely.
  – A measurement of few MeV neutrinos at very short baseline ($\sim 10$ m) would be interesting.
• Future intermediate/long-baseline reactor antineutrino experiments may be used for a precision measurement of $\theta_{12}$ (using baseline from $\Delta m^2_{21} = \Delta m^2_{\text{sol}}$).
Backups
## Double Chooz systematic uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Chooz</th>
<th>Double-Chooz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor-induced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu$ flux and $\sigma$</td>
<td>1.9 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Reactor power</td>
<td>0.7 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Energy per fission</td>
<td>0.6 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Detector-induced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid angle</td>
<td>0.3 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Volume</td>
<td>0.3 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Density</td>
<td>0.3 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>H/C ratio &amp; Gd concentration</td>
<td>1.2 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Spatial effects</td>
<td>1.0 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Live time</td>
<td>------</td>
<td>0.25 %</td>
</tr>
<tr>
<td>Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 7 to 3 cuts</td>
<td>1.5 %</td>
<td>0.2 - 0.3 %</td>
</tr>
<tr>
<td>Total</td>
<td>2.7 %</td>
<td>&lt; 0.6 %</td>
</tr>
</tbody>
</table>

Two "identical" detectors, Low bkg
Distance measured @ 10 cm + monitor core barycenter
Precise control of detector filling
Accurate T control (near/far)
Same scintillator batch + Stability
Identical detectors and monitoring
Special electronic systems and monitoring
Simplified cuts due to detector design
From Detection Cross Section to $\bar{\nu}_e$ Energy Spectrum

$$\sigma_{tot}(E_e) \approx \frac{2\pi^2 h^3}{m_e^5 c^7 f \tau_n} \cdot p \cdot E_e \approx \frac{p \cdot E_e}{1 \text{MeV}^2} \cdot 10^{-43} \text{ cm}^2$$

In lowest order, assuming infinitely heavy neutron. No nuclear matrix element involved. Cross section directly linked to measured neutron life time and phase space. Use cross section by Vogel & Beacom:

$\sigma$ to order $1/M$, radiative corrections, weak magnetism $\rightarrow$ few % correction Cross section accurate to 0.2%

Neutrinos with $E<1.8$ MeV are not detected
Reactor Measurements of $\theta_{13}$

- $3.8 \text{ GW} \rightarrow 7 \times 10^{20} \nu_e/s$
  - ~800 events / yr / ton at 1500 m away
- Reactor spectrum peaks at 3 to 4 MeV
- Oscillation Max. for $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$
  - at $L \sim 1000 - 1500$ m
RENO Detector Construction & Closing (Jan. 2011)
Summary of RENO Status

• Construction of both near and far detectors are completed in Feb. 2011.

• All the liquids including Gd loaded liquid scintillator are produced and filled as of July 5, 2011.

• Dry runs were performed to check PMT and DAQ in March ~ May, 2011.

• Background data-taking has been made since the middle of June, 2011.

• Commissioning shifts and calibration efforts are on progress.

• Regular data-taking is expected to begin from August 1, 2011.
Daya Bay Anti-neutrino Detector Assembly