It’s Chooz Time!
Case Western Reserve University
May 4, 2011

Lindley Winslow
The Double Chooz Collaboration:

APC Paris CNRS/IN2P3, CEA/DSM/IRFU, SPP, SPhN, SEDU, SIS, SENAC, IPHC Strasbourg, Subatech Nantes, ULB

INR RAS, IPC RAS, RRC Kurchatov

Aachen U., Hamburg U., MPIK Heidelberg, TU München, EKU Tübingen

HIT, Kobe U., Niigata U., Tohoku U., TGU, TIT, TMU

CIEMAT Madrid


Sussex U.

CBPF, UNICAMP
The Experiment:
The Standard Model of Particle Interactions

Three Generations of Matter

I  II  III

Quarks

Leptons

Force Carriers

u  c  t  γ

d  s  b  g

ν_e  ν_μ  ν_τ

e  μ  τ

W
Neutrinos have mass!
We know this because of Neutrino Oscillation:

What we call the electron neutrino is actually a mixture of three mass states.

\[
\nu_e = \nu_{e1} + \nu_{e2} + \nu_{e3}
\]

Alternatively, we can say that each mass state is a mixture of the three flavors.

\[
\nu_1 = \nu_e + \nu_\mu + \nu_\tau
\]
Neutrinos are defined by their flavor....

but it’s mass that propagates through space...

From Celebrating the Neutrino, LANL
\[ P_{\text{survival}} = 1 - \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]
$n \rightarrow p + e^- + \bar{\nu}_e$
A Long History of Reactor Neutrinos

Neutrinos Oscillate!

\[ P_{\text{survival}} = 1 - \sin^2 2\theta \sin^2 \left( \frac{1.27\Delta m^2 L}{E} \right) \]
The Big Picture

\[ U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\theta_{23} & s\theta_{23} \\ 0 & -s\theta_{23} & c\theta_{23} \end{pmatrix} \begin{pmatrix} c\theta_{13} & 0 & s\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s\theta_{13}e^{i\delta} & 0 & c\theta_{13} \end{pmatrix} \begin{pmatrix} c\theta_{12} & s\theta_{12} & 0 \\ -s\theta_{12} & c\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\xi_1/2} & 0 & 0 \\ 0 & e^{i\xi_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

Atmospheric
K2K, MINOS

Solar + KamLAND

Does it violate CP?

Is it Majorana?

But first that pesky mixing angle!
This is Quark Mixing

This is Neutrino Mixing
What are the current best limits?

Chooz Bound: $\sin^2 2\theta_{13} < 0.21$

Global Analysis: $\sin^2 2\theta_{13} = 0.04-0.12$
What next?

Long Baseline Does It All! 
$\theta_{13}$, CP Violation, Mass Hierarchy....

Unfortunately Long Baseline does it all ...

T2K  

NOVA
\[ P_{\text{mat}} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 (\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2 \]

\[ \mp \sin \delta \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \Delta_{31} \frac{\sin (\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31} \frac{\sin (aL)}{(aL)} \Delta_{21} \]

\[ + \cos \delta \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \cos \Delta_{31} \frac{\sin (\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31} \frac{\sin (aL)}{(aL)} \Delta_{21} \]

\[ + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 (aL)}{(aL)^2} \Delta_{21}^2. \]
What you need is a clean measurement of $\theta_{13}$. ...
The Most Complicated Formula:

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
+ \frac{1}{2} \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{2E} \sin^2 \frac{\Delta m^2_{21} L}{2E} \\
- \left( \cos^4 \theta_{13} \sin^2 2\theta_{12} + \sin^2 \theta_{12} \sin^2 2\theta_{13} \cos \frac{\Delta m^2_{31} L}{2E} \right) \sin^2 \frac{\Delta m^2_{21} L}{4E}.
\]

\[
E = 3\text{MeV} \\
\sin^2 2\theta_{13} \sim 0.2 \\
\Delta m^2_{31} = 2.5 \times 10^{-5}\text{eV}^2
\]
And Really....

\[ P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \]

Near+Far is key and we will come back to that... for now reactors provide a very clean measurement.

\[ E=3\text{MeV} \]
\[ \sin^2 2\theta_{13} \sim 0.2 \]
\[ \Delta m_{31}^2 = 2.5 \times 10^{-5}\text{eV}^2 \]
Reactors are still cool.
The Experiment:
Where in the World is Chooz?
The Detector:
Anti-Neutrino Detection - Inverse Beta Decay

Event #1 $E_e = E_{\nu} - 0.8\text{MeV}$

Event #2 $E_\gamma \sim 8\text{MeV}$
Backgrounds:

- Accidental coincidences.
- Fast neutrons.
- Beta delayed n emitters, $^9\text{Li}$ and $^8\text{He}$.
The Detector:

Calibration glove box
Outer veto: plastic scintillator strips
Shielding: 15 cm steel
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

⇒ 50 Neutrinos a day at 1km!
Why the two detectors?

<table>
<thead>
<tr>
<th></th>
<th>Chooz</th>
<th>Double Chooz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v flux and spectrum</td>
<td>1.9%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Reactor Power</td>
<td>0.7-2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Angle</td>
<td>0.3%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Target Mass</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 and Gd ratio</td>
<td>1.2%</td>
<td>&lt;0.2%</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>&lt;0.2%</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 3-7 cuts.</td>
<td>1.5%</td>
<td>0.2-0.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2.7%</td>
<td>&lt;0.6%</td>
</tr>
</tbody>
</table>
Predicted Sensitivity:

\[ \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]

\[ \sigma_{\text{sys}} = 2.5\% \quad \sigma_{\text{sys}} = 0.6\% \]

Excluded by CHOOZ

Limit \( \sin^2 2\theta_{13} \)

G. Mention et al. arXiv:0704.0498v2
And then there were three:
The Three Experiments:

<table>
<thead>
<tr>
<th></th>
<th>Double Chooz</th>
<th>Daya Bay</th>
<th>RENO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Cores</td>
<td>2 Cores</td>
<td>6 Cores</td>
<td>6 Cores</td>
</tr>
<tr>
<td>Total Power</td>
<td>8.54 GW</td>
<td>11.6 GW†</td>
<td>16.4 GW</td>
</tr>
<tr>
<td>Target Mass</td>
<td>8.24 tons</td>
<td>20 tons</td>
<td>15 tons</td>
</tr>
<tr>
<td>Near Distance</td>
<td>400m</td>
<td>300-500m†</td>
<td>290m</td>
</tr>
<tr>
<td>Near Overburden</td>
<td>115 m.w.e</td>
<td>~100 m.w.e†</td>
<td>130 m.w.e</td>
</tr>
<tr>
<td>Far Distance</td>
<td>1.05km</td>
<td>1.6-1.9km</td>
<td>1.4km</td>
</tr>
<tr>
<td>Far Overburden</td>
<td>300 m.w.e.</td>
<td>350 m.w.e</td>
<td>460 m.w.e.</td>
</tr>
<tr>
<td>Events per Day</td>
<td>425/43</td>
<td>1600/400†</td>
<td>5000/100</td>
</tr>
</tbody>
</table>

† Daya Bay will increase to 17.4GW in 2011, has two near sites, and uses multiple detectors per site.
Hunting $\theta_{13}$:

(Disclaimer, all comparisons are of my own imagination and do not reflect the views of my group, collaboration, etc.)

\[
\sin^2 2\theta_{13} \sim 0.01 \quad \sin^2 2\theta_{13} \sim 0.02 \quad \sin^2 2\theta_{13} \sim 0.03
\]
Predicted Sensitivity:

\[ \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]

Limit \( \sin^2 \theta_{13} \)

Excluded by CHOOZ

G. Mention et al. arXiv:0704.0498v2
A Few More Details on Reactor Anti-Neutrinos:

- $2 \times 10^{20}$ anti-neutrinos per s per GW$_{th}$
Simulating fission rates...
How do reactors work?
Fuel is arranged in assemblies.
The assemblies are inserted into the reactor vessel.
Enter the Dragon....

• Dragon is a 2D assembly code that directly solves the neutron transport equations.

• We input detailed geometry and fuel compositions and then evolve the reactor in time.

• We then sum up the results of each assembly to get the total number of fissions in the core.

• We also do these calculations with MURE (a MCNP based full core simulation.)
Understanding the performance....

The Takahama reactor published the detailed power history and the chemical analysis of several fuel rods - Takahama Benchmark.

DRAGON and MURE are performing well!
Using SONGs Data to Verify Reactor Models:

**San Onofre Nuclear Generating Station**

**SONGS reactor:** 3.438 GWth output

**SONGS detector:** 0.64 ton liquid scintillator doped with Gd

Data from LLNL and Sandia NL
A Switch!
Using Neutrino Detectors to Monitor Reactors....

![Graph showing the removal of 250 kg of $^{239}$Pu and addition of 1500 kg of $^{235}$U during cycle 13, followed by a reactor outage, and the start of cycle 14. The graph compares the predicted and observed rates of detected antineutrinos and reactor power.]
The Other half of your prediction...the Spectra

\[ S_{\text{tot}}(E) = \sum_{k=^{235}\text{U}, \, ^{238}\text{U}, \, ^{239}\text{Pu}, \, ^{241}\text{Pu}} \alpha_k \times S_k(E) \]

Number of Fissions per Isotope

Anti-neutrino spectra from the Isotopes
Where did the spectra come from?

The beta spectrum of $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ were measured using a spectrometer.

Now you use energy conservation to extract the neutrino spectrum.
Updating the Extraction....

Shift of 3.1%, Oh My!

Lindley Winslow
You may now look at the blue line....

All the experiments are now low.
Is this evidence for sterile neutrinos?

The blue line is a fit to a 4th neutrino state with a mass splitting of $>1\text{eV}^2$. 

arXiv:1101.2755v4
Predicted Sensitivity:

\[ \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]

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

G. Mention et al. arXiv:0704.0498v2
Double Chooz Construction:

May 2008

February 2009
Just because it has to be mentioned:

Gd-Loaded Scintillator $\Rightarrow$ Stable $>2$ years!
The Electronics:

- Signal + HV on one cable.
- Frontend cards shape pulses, corrects baseline and integrates charge.
- Analog Trigger triggers on photoelectron equivalent.
- 500MHz Caen digitizers record pulses.
- Subset of PMTs sent to second system to record muon events.
Single Photo-Electron Data:

channel = 53, trigger_id = 46

Amplitude: <IPE> ~ 8ADC counts
Charge: <IPE> ~ 60 DUQ (integrated ADCx2ns)
Inner Detector Muon Event
Inner Veto Muon Event

DC Preliminary
Inner Detector Event
Muon Event Rate Through the Inner Detector

Constant: $7.349 \pm 0.010$
Slope: $-0.03891 \pm 0.00027$

Double Chooz Preliminary

Lindley Winslow
Predicted Sensitivity:

\[ \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]

G. Mention et al. arXiv:0704.0498v2
More Things.....
Spectral Evolution:

![Graph showing spectral evolution over anti-neutrino energy](image)

- **Day 0**
What does a 0.2% systematic mean?

• Think about temperature and the determination of the number of protons targets.
• The coefficient of thermal expansion is $1 \times 10^{-3}$ m$^3$/K.
• The 0.2% systematic on the proton number 2°C change in temperature.
• That's a fairly large temperature change for the hall ... but possible if the cooling of the electronics fails.

Before that we have an issue that a 0.2°C change in the target temperature leads to a 50cm change in level in the chimney region.
Thermal Issues:

PMTs dissipating 70W+12.5W =82.5W
Thermal Issues - Convection is your friend.
The Estimated Background Rates:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Site</th>
<th>Accidental</th>
<th>Background</th>
<th>Correlated</th>
<th>$^9\text{Li}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHOOZ</td>
<td>Rate ($d^{-1}$)</td>
<td>0.42 ± 0.05</td>
<td>1.01 ± 0.04 (stat) ± 0.1 (sys)</td>
<td></td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>Rate ($d^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Far bkg/ν</td>
<td>1.6%</td>
<td>4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Systematics</td>
<td>0.2%</td>
<td>0.4%</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Chooz</td>
<td>Rate ($d^{-1}$)</td>
<td>0.5 ± 0.3</td>
<td>1.5 ± 0.8</td>
<td>0.2 ± 0.2</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>Far bkg/ν</td>
<td>0.7%</td>
<td>2.2%</td>
<td>0.2%</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>Systematics</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
<td>0.2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.7%</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>Rate ($d^{-1}$)</td>
<td>5 ± 3</td>
<td>17 ± 9</td>
<td>1.3 ± 1.3</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Near bkg/ν</td>
<td>0.5%</td>
<td>1.7%</td>
<td>0.13%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>Systematics</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
<td>0.2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2%</td>
</tr>
</tbody>
</table>