Double Chooz

Searching for $\theta_{13}$ with reactor neutrinos

XLVI$^{TH}$ Rencontres de Moriond
Electroweak Interactions and Unified Theories
March 2011, La Thuile

Pau Novella Garijo (CIEMAT)

For the Double Chooz Collaboration

Moriond 2011, La Thuile
Overview

- Reactors neutrinos towards $\theta_{13}$
- The Double Chooz experiment
- The new-born detector
- Taking the most from Double Chooz
Measuring the oscillation

\[ \Delta m^2_{ij} \equiv m_i^2 - m_j^2 \]
Exploring the neutrino mixing

Oscillation parameters: \((\theta_{12}, \theta_{13}, \theta_{23}), (\Delta m^2_{21}, \Delta m^2_{31}), \delta\)

\[ \nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{k L} \]

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{21} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
e^{i\alpha_1} & 0 & 0 \\
0 & e^{i\alpha_2} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

Atmospheric sector

interference sector

Solar sector

\(\beta\beta0\nu\)
What's next?

- Experimental results:
  - $(|\Delta m^2_{\text{atm}}|, \theta_{\text{atm}}) \rightarrow \text{Minos and Super-K}$
  - $(\Delta m^2_{\text{sol}}, \theta_{\text{sol}}) \rightarrow \text{Kamland and solar data}$

- $\sin^2(2\theta_{13}) < 0.15$ from CHOOZ: $\delta$?

- $\Delta m^2 \sim 2.4 \times 10^{-3} \text{ eV}^2$
  - $\theta \sim 45^\circ$

- $\Delta m^2 \sim 7.6 \times 10^{-5} \text{ eV}^2$
  - $\theta \sim 33^\circ$

- Measurement of $\delta_{\text{cp}}$
- Sign of $\Delta m^2_{\text{atm}}$ (hierarchy)
- Design of next experiments
Why reactor neutrinos?

- No parameter correlations
- Nearly pure $\bar{\nu}_e$ beam
- Low energy
- No matter effects
- Cheap, as source exists
- High flux and large xsection

In contrast to accelerator experiments...

\[
P_{ee}(E_{\bar{\nu}_e}, L, \Delta m^2_{31}, \theta_{13}) = 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{1.27 \Delta m^2_{31}[10^{-3} \text{ eV}^2]L[\text{km}]}{E_{\bar{\nu}_e}[\text{MeV}]} \right)
\]
The Double Chooz Experiment

Ready!

2012

2x2.45 GW

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The Double Chooz Collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC
ULB

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

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst Tech.

Russia
INR RAS
IPC RAS
RRC Kurchatov

Spain
CIEMAT-Madrid

UK
Sussex

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/
Setting up the experiment

Reactor neutrinos:

\[ \langle E_\nu \rangle \sim 4 \text{ MeV} \]

Solar sector

Systematics!

Oscillation!

400 m

1050 m
Detecting reactor neutrinos

- **Target:** scintillator + n-catcher (Gd)
- **Detector:** PMTs

**IBD:** \( \bar{\nu}_e + p \rightarrow e^+ + n \)

\[ E_{\text{vis}} = E_{e^+} + m_c \sim E_{\bar{\nu}_e} - \Delta + m_c \]

**Prompt signal** (1-8 MeV)

**Delayed signal** (30 μs, 8 MeV)

Th: 1.8 MeV. Disappearance!

**\( E_\nu \) spectrum**

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Expected oscillation signal

- $8 \times 10^{29}$ free protons
- Detection efficiency 80%

3 years:
- $\sim 50,000$ events expected

Deficit!

Energy dependent!

Toy Monte Carlo
Backgrounds

Uncorrelated:
- Radioactivity + fast neutrons

Correlated:
- Fast neutrons: p recoil + n capture
- cosmogenic isotopes: n-β decay

Background measurements on site!
Double Chooz Detectors

Glove box

μ Outer Veto

Inner Veto

Near and Far Detectors are identical

Inner Detector

Buffer

Gamma Catcher

Target

are identical
Double Chooz Detectors

**Target**
- 10.3 m$^3$ acrylics vessel
- Gd-doped Scintillator
- Detect neutrinos

**Buffer**
- 110 m$^3$ stainless steel
- 390 10” PMTs
- Mineral oil
- isolation

**γ Catcher**
- 23 m$^3$ acrylics vessel
- Scintillator (no Gd)
- Calorimetry

**Inner Veto**
- 90 m$^3$ stainless steel
- 78 8” PMTs
- Scintillator
- Detect muons
Calibration Systems

3 Calibration sources:
- Natural: H n-capture peak
- Radioactive sources
- Laser and LED system
The New Born Detector

Far detector built and filled by the end of 2010
Far Detector Hall

Electronics Hut

Outer Veto

Far Detector

Glove Box
The Inner Veto
The Inner Detector

- The Buffer
- 10” PMT (x390)
- The Acrylic vessels
Closing The Detector

The Buffer Lid

The Lid PMTs
Feeding The Detector

The Filling Station

Measuring the liquid level
The Shield

- PMT Splitters
- Chimney
- Electronics Hut
- Iron Shield

- To be installed:
  - Outer Veto
  - Globe Box
The Detector Brain

- **ID + IV electronics+online chain**

- **DAQ and trigger up and running**

- **Outer veto: PMT + maroc2 chip**
Seeing the light

Commissioning: January – March 2011
First PEs @ Chooz

- Summer 2010: first PEs detected in an empty detector

![Graph showing ADC counts over time with a peak amplitude of approximately 8 ADC counts. The graph is labeled PRELIMINARY (DC June 2010).]
Scintillator Time Response

2010: reconstructed scintillator time response in partially filled detector
Electronics noise

- 2010: stability of the electronics

- **4 µs Baseline in Channel 0**
  - Sample @ 500 MHz
  - up to 4 µs per channel

- **Baseline mean in Channel 0**

- Electronics noise very low and stable
Inner Detector Events

- 2011: first events with a filled detector

ID Contained Event

ID Waveforms

DC Preliminary

Few PEs
Detecting the muons
Muons in the Inner Detector

μ in ID

μ ID Waveforms

O(100) PEs
Muon Rate @ Inner Veto

First estimation of muon rate: 38.8 trigger / second
Taking the most from DC

Data taking for first analysis: April 2011

\[ \theta_{13} \]
Improving CHOOZ

\[ \sin^2(2\theta_{13}) < 0.15 \]
\[ (\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2) \]

**Statistical error:**

<table>
<thead>
<tr>
<th></th>
<th>CHOOZ</th>
<th>Double Chooz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Volume</td>
<td>5.55 m3</td>
<td>10.3 m3</td>
</tr>
<tr>
<td>Data Taking</td>
<td>Few months</td>
<td>3-5 years</td>
</tr>
<tr>
<td>Statistical Error</td>
<td>2.8%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

**Systematics:**

<table>
<thead>
<tr>
<th></th>
<th>CHOOZ</th>
<th>Double Chooz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Flux</td>
<td>2%</td>
<td>--</td>
</tr>
<tr>
<td>Number of protons</td>
<td>0.8%</td>
<td>0.2</td>
</tr>
<tr>
<td>Systematic Error</td>
<td>2.7%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
Two Phases

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic</th>
<th>DC Phase I</th>
<th>DC Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>Production σ</td>
<td>1.9%</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Core powers</td>
<td>2.0%</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Energy per fission</td>
<td>0.6%</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Solid angle</td>
<td>--</td>
<td>0.1%</td>
</tr>
<tr>
<td>Detector</td>
<td>Number of protons</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>Gd concentration</td>
<td>0.3%</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Detection σ</td>
<td>0.1%</td>
<td>--</td>
</tr>
<tr>
<td>Analysis</td>
<td>Event selection</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&lt; 2.8%</strong></td>
<td><strong>&lt; 0.6%</strong></td>
<td></td>
</tr>
</tbody>
</table>

- **Phase I: Far Detector only**
  - 2011 *(Now!!!)*
  - Sensitivity limited by the uncertainties in reactor neutrino fluxes

- **Phase II: Far and Near Detectors**
  - 2012
  - Sensitivity limited by Detector relative normalization and energy scale
Double Chooz Sensitivity

- Far Only detectors:
  \[ \sigma_{\text{sys}} = 2.6\% \]

- Near and Far detectors:
  \[ \sigma_{\text{sys}} = 0.6\% \]

- Limit to \( \sin^2(2\theta_{13}) \) @ 90\% CL:
  \( < 0.15 \)

- Exposure time (years):
  \( < 0.15 \)
Double Chooz will search for $\sin^2(2\theta_{13})$ down to 0.03

- The quest has just begun!
  - The far detector was built and filled by December 2010
  - Commissioning period: January 2011 – March 2011
  - Detector yields good and stable performance
  - Far Detector is almost ready to take physics data
  - Results improving CHOOZ limit to $\theta_{13}$ quite soon!
Thank you!

Photo: Lola Garrido
Reactors as \( \nu \) source

\( \nu \) come from fission products...

- **High flux**: \( 1\text{GW}_{\text{th}} \sim 2 \times 10^{20} \frac{\nu_e}{s} \)

- \( \nu \) Flux depends on fuel composition:
  - Flux derived and parametrized from \( \beta \) decay measurements...
  - Not measured
  - Flux known to only 2%

Palo Verde

\[ \text{Flux}(\text{fissions/s}) \]

\[ \begin{align*}
  233\text{U} & \quad \text{•} \\
  234\text{U} & \quad \text{□} \\
  239\text{Pu} & \quad \text{▲} \\
  240\text{Pu} & \quad \text{▼} \\
  241\text{Pu} & \quad \text{○} \\
  242\text{Pu} & \quad \text{□} \\
\end{align*} \]
What we know about $\theta_{13}$

- Past reactor experiments...

- From CHOOZ:
  \[ \sin^2(2\theta_{13}) < 0.15 \]
  \[ \Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]
Comparing the experiments

<table>
<thead>
<tr>
<th>Power</th>
<th>Target</th>
<th>Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.6 GW</td>
<td>8.24 tons</td>
<td>400 m/115 wme</td>
<td>1.05 km/300 wme</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power</th>
<th>Target (x2x4)</th>
<th>Near (x2)</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.4 GW</td>
<td>20 tons</td>
<td>360-500 m/ 260 mwe</td>
<td>1.6-2.0 km/910 wme</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power</th>
<th>Target</th>
<th>Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.3 GW</td>
<td>16 tons</td>
<td>290 m/130 wme</td>
<td>1.38 km/460 wme</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{stats}}$ (%)</th>
<th>$\sigma_{\text{sys}}$ (%)</th>
<th>$s_{13\text{lim}}^2$ (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Chooz</td>
<td>0.5</td>
<td>0.6</td>
<td>0.03</td>
</tr>
<tr>
<td>Reno</td>
<td>0.3</td>
<td>0.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>0.2</td>
<td>0.4</td>
<td>0.01</td>
</tr>
</tbody>
</table>

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Calibration

Calibration Strategy:
- Redundancy of several calibration systems
- Cross-check and accurate understanding of the systematics

Calibration Goals:
- PMT+Electronics Gain and Timing
  - Embedded LED system and deployed isotropic laser
- Liquid Scintillator optics and stability
- Detector stability
  - Embedded LED system and deployed isotropic laser
- Energy scale
  - Radioactive sources (137Cs, 22Na, 60Co, ...)
  - n-capture on H
- Gd n-capture efficiency
  - Neutron sources (252Cf Am-Be, tagged/un-tagged)
- 3D response
  - Deployment of sources along Z-axis (fish-line)
  - Calibration arm off Z-axis
  - Deployment of sources in GC and Buffer guide lines