Commissioning the Double Chooz detector

Jaime Dawson, APC

Les Rencontres de Physique de la Vallee d'Aoste, 2011
Contents

● Brief reminder
  – Reactor experiments
  – Double Chooz concept
● Neutrino signals and backgrounds
● Double Chooz detectors
  – Far Detector (Running!)
● Sensitivity
● Conclusion
Three Neutrino Mixing

Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix

- 3 mixing angles
- 1 CP phase

\[ U = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \]

- solar
- atmospheric

- 2 mass splittings \( \Delta m^2_{ij} \)
- We don't know \( \theta_{13}, \delta_{cp} \) and sign of \( \Delta m^2_{31} \)
Reactor Experiments

\[ P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 L [\text{km}] \Delta m^2_{31} [10^{-3} \text{eV}^2]}{E [\text{MeV}]} \right) \]

\[ - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{1.27 L [\text{km}] \Delta m^2_{21} [10^{-3} \text{eV}^2]}{E [\text{MeV}]} \right) \]

**Chooz:** \[ R = 1.01 \]

\[ \pm 2.8\% \text{ (stat)} \]

\[ \pm 2.7\% \text{ (syst)} \]

\[ \sin^2 2\theta_{13} < 0.13 \text{ (90\% C.L)} \]

Fogli et al., arXiv: 0805.2517

![Graph showing the probability of neutrino oscillation](image)

**$E_\nu = 4 \text{ MeV}$**

- \[ \sin^2 2\theta_{13} = 0 \]
- \[ \sin^2 2\theta_{13} = 0.1 \]

**Graph showing the relationship between distance and probability**


Jaime Dawson, APC Paris
Reactors $\theta_{13}$ Experiments

- Disappearance of anti-neutrinos (independent of $\delta_{cp}$ and sign of $\Delta m_{31}$, weak dependence of $\Delta m_{21}$)
- Short distances, $\sim$MeV signals (no matter effects)
Double Chooz collaboration

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

Web Site: www.doublechooz.org/
Concept

- 2 'identical' detectors
  - **Near**
    - 410 m
    - 115 m.w.e
    - ~500 ν/day
  - **Far**
    - 1050 m
    - 300 m.w.e
    - ~70 ν/day

- Systematics on reactor power, neutrino spectrum, cross-section and detection are insignificant for a relative measurement
Neutrino Signal

- Detect anti-neutrinos via inverse beta decay
  \[ p + \bar{\nu} \rightarrow n + e^+ \]
- In Gd- loaded scintillator
  \- e^+ signal 1-8MeV
  \- e^+ e^- annihilation(2 \times 511 \text{ keV})
  \[ E_{\text{vis}} = E_\nu - (M_n - M_p) + m_e \]
  \- Delayed neutron capture on
    \- Gd \sim 30 \mu s \sim 8 \text{ MeV (>80%)}
    \- H \quad 2.2 \text{ MeV}
Backgrounds

Our signal is a positron followed by a neutron capture (2 triggers)

Accidental

- Dominant source of accidentals
  - Radioactivity (from PMT)
- Solution - we aim for a singles rate of less than 5/s above 0.7 MeV
  [expect far: 2 day$^{-1}$ near: 11 day$^{-1}$]
  - Stringent radiopurity constraints

<table>
<thead>
<tr>
<th></th>
<th>$^{40}$K</th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>$^{60}$Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target LS</td>
<td>$10^{-10}$</td>
<td>$10^{-13}$</td>
<td>$10^{-13}$</td>
<td>—</td>
</tr>
<tr>
<td>Target Acrylics</td>
<td>$10^{-8}$</td>
<td>$10^{-11}$</td>
<td>$10^{-11}$</td>
<td>—</td>
</tr>
<tr>
<td>GC LS</td>
<td>$10^{-10}$</td>
<td>$10^{-13}$</td>
<td>$10^{-13}$</td>
<td>—</td>
</tr>
<tr>
<td>GC Acrylics</td>
<td>$10^{-8}$</td>
<td>$10^{-11}$</td>
<td>$10^{-11}$</td>
<td>—</td>
</tr>
<tr>
<td>Buffer Oil</td>
<td>—</td>
<td>$10^{-12}$</td>
<td>$10^{-12}$</td>
<td>—</td>
</tr>
<tr>
<td>Buffer Vessel</td>
<td>—</td>
<td>$10^{-9}$</td>
<td>$10^{-9}$</td>
<td>15</td>
</tr>
<tr>
<td>Veto LS</td>
<td>—</td>
<td>$10^{-10}$</td>
<td>$10^{-10}$</td>
<td>—</td>
</tr>
</tbody>
</table>

Correlated

- Cosmogenics ($\beta$-neutron)
  - Li-9 and He-8 long lived
    [expect far: 1.5 day$^{-1}$ near: 4 day$^{-1}$]
- Fast neutrons
  - Proton Recoil (positron-like signal) followed by neutron capture
    [expect far: 0.2 day$^{-1}$ near: 0.5 day$^{-1}$]
- Caused by muons!

Cartoon

Jaime Dawson, APC Paris
The Laboratories

- Outer Muon Veto
  Plastic scintillator strips with x,y positioning

- Electronics

- Glove Boxes and Calibration systems
The Detectors

**TARGET:** (th=2.3 m)
- Acrylic vessel (th=8 mm)
- 10.3 m$^3$ LS doped with 1 g/l Gd

**Acrylic vessels ➔ «hardware» definition of fiducial volume**

**GAMMA CATCHER:** (th. = 0.55 m)
- Acrylic vessel (th=12 mm)
- 22.6 m$^3$ LS (identical to target)

**Buffer:** (th.=1.05 m)
- Stainless steel vessel (th = 3 mm)
- 114.2 m$^3$ mineral oil
- 390 PMTs (10 inches)

**Inner VETO:** (th = 0.5 m)
- Steel vessel (th = 10 mm)
- ~80 m$^3$ LS
- 78 PMTs

**OTHER SYSTEMS**
- Outer Muon Veto System
- Calibration Systems
- Glove Boxes

**SHIELDING**
@ far site: 15 cm Steel
~300 t
Muon Tracking

- **Outer Veto**
  - Tag near miss muons
  - Entry point of any muon
- **Inner Veto**
  - Efficient tag of muons and secondaries
  - Track muon
- **Muon Electronics**
  - Attenuated output of Inner Detector PMTs
  - Track muon
Calibration

Fish-line (Z-axis)

Articulated Arm

Embedded LED calibration system 385, 420, 470 nm

Glove Box

GC guide Tube

Buffer guide Tube
Far Detector - history

Lab for the original Chooz experiment

Jaime Dawson, APC Paris
Far Detector – Filled and Shielded
Far Detector
Electronics

Front End
- 8-channel custom-built
- Amplified low noise outputs to Waveform Digitisers
- Summed and stretched output to Trigger

Trigger
- custom-built trigger system (VME)
- Trigger based on analog sum on groups of PMTs.
  Gives Particle ID based on Energy

Waveform Digitisers
- 500 MHz 8-bit flash ADC (developed with Caen – V1721X)
- Dead-time-less (for our expected event rate)
- In-house firmware allows choice of event size based on Info from trigger
  Time between consecutive events
Neutrino DAQ

• Waveform Digitisers
  – Digitise all 390 Inner Detector and 78 Inner Veto PMTs
  – 60 FADC cards (split over 4 VME crates)

• Taking data now!
Far Detector - scintillation

Average light time response from a run during the filling of the Inner Detector

Uncalibrated Double Chooz

Jaime Dawson, APC Paris
Far Detector - Events!

Event contained in Inner Detector
Far Detector - Events!

Muon in Inner Detector

Muon in Inner Veto

DC Preliminary

Jaime Dawson, APC Paris
Status: Near Lab

Near Lab to be completed by March 2012

Jaime Dawson, APC Paris
Improvements on Chooz

Chooz: $R = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (syst)}$

- **Statistical**
  - Large Volume
    - $5.55m^3 \rightarrow 10.3m^3$
  - Run Time
    - ~months $\rightarrow$ 3-5 yrs
  - Number of Events
    - 2700 $\rightarrow$ 60,000 (far in 3 yrs)

  $\triangleright$ 0.4 %

- **Systematic**
  - Reactor
  - Detector
  - Analysis

  $\triangleright$ < 0.6 %
**Systematics: Analysis**

- Lower threshold (see all of positron spectrum)
- Target Acrylic vessel (no fiducial volume cut)

<table>
<thead>
<tr>
<th>selection cut</th>
<th>CHOOZ rel. error (%)</th>
<th>Double-CHOOZ rel. error (%)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>positron energy*</td>
<td>0.8</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>positron-geode distance</td>
<td>0.1</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>neutron capture</td>
<td>1.0</td>
<td>0.2</td>
<td>Cf calibration</td>
</tr>
<tr>
<td>capture energy containment</td>
<td>0.4</td>
<td>0.2</td>
<td>Energy calibration</td>
</tr>
<tr>
<td>neutron-geode distance</td>
<td>0.1</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>neutron delay</td>
<td>0.4</td>
<td>0.1</td>
<td>—</td>
</tr>
<tr>
<td>positron-neutron distance</td>
<td>0.3</td>
<td>0 – 0.2</td>
<td>0 if not used</td>
</tr>
<tr>
<td>neutron multiplicity*</td>
<td>0.5</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>combined*</td>
<td>1.5</td>
<td>0.2-0.3</td>
<td>—</td>
</tr>
</tbody>
</table>

*average values

* Easier to control near vs far than absolute
## Systematics

<table>
<thead>
<tr>
<th></th>
<th>Chooz</th>
<th>Double-Chooz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor-induced</strong></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><strong>Detector-induced</strong></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><strong>Analysis</strong></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><strong>Total</strong></td>
<td>2.7 %</td>
<td>&lt; 0.6 %</td>
</tr>
</tbody>
</table>

Two "identical" detectors, Low bkg

Precise target mass measurement

Accurate T control (near/far)

Same scintillator batch + Stability

Spill in/out compensate to ~1%

Difference near/far is relevant! (see previous slide)
Sensitivity

Double Chooz target sensitivity

\[ \sin^2 2\theta_{13} \sim 0.03 \text{ (for } \Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2) \]
Conclusion

• Far detector is Running!
• With far
  – Achieve a sensitivity of $\sin^2 2\Theta_{13} \sim 0.06$ with one year of data
• With near and far
  – measure $\sin^2 2\Theta_{13}$ to $3\sigma$ if $\sin^2 2\Theta_{13} > 0.05$,
  – or exclude $\sin^2 2\Theta_{13}$ down to 0.03 (90% C.L) with 3 years of running
• Expect interesting results from Double Chooz soon!
backups
Complementary to Beam experiments

- Example of Double Chooz results compared to T2K
  - Assume full power for T2K
  - 2 years of 2 detector (DC)
  - Full $=90\%$, dashed $3\sigma$

- No dependence on $\delta_{CP}$ (reactor)
Calibration Sources

- Objectives
  - Relative neutrino detection efficiency between near and far < 0.5%
  - Positron/gamma energy scale to 1%
  - Neutron energy scale to 25%
Neutrino DAQ

ReadOut Processor

ROP: Trigger

ROP: FADCs

ROP: FADCs

VME

Neutrino DAQ

Read Out Processor

DATA

EVENTBUILDER

DATA

EVENTBUILDER

Muons

TRIGGER

FADCs

FADCs

FADCs
Total systematics: \(~\sim 0.6\%\
Statistics: 60000 neutrino events @ Far Detector
Scintillator Liquid Storage and Handling (Oct 08)
Spectrum

- Two independent measures
  - Normalisation
  - Spectral Distortion
## Background Comparison

<table>
<thead>
<tr>
<th>Detector</th>
<th>Site</th>
<th>Accidental Materials</th>
<th>PMTs</th>
<th>Fast n</th>
<th>Correlated $\mu$-Capture</th>
<th>$^9$Li</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHOOZ (24 $\nu$/d) Far</td>
<td>Rate ($d^{-1}$)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>Rate ($d^{-1}$)</td>
<td>0.42 ± 0.05</td>
<td>1.01 ± 0.04 (stat) ± 0.1 (sys)</td>
<td>4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>bkg/$\nu$</td>
<td>1.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Systematics</td>
<td>0.2%</td>
<td></td>
<td></td>
<td></td>
<td>0.4%</td>
</tr>
<tr>
<td>Double Chooz (69 $\nu$/d) Far</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>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>bkg/$\nu$</td>
<td>0.7%</td>
<td>2.2%</td>
<td>0.2%</td>
<td>&lt;0.1%</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>
<td>0.7%</td>
</tr>
<tr>
<td>Double Chooz (1012 $\nu$/d) Near</td>
<td>Rate ($d^{-1}$)</td>
<td>5 ± 3</td>
<td>17 ± 9</td>
<td>1.3 ± 1.3</td>
<td>0.4</td>
<td>9 ± 5</td>
</tr>
<tr>
<td></td>
<td>bkg/$\nu$</td>
<td>0.5%</td>
<td>1.7%</td>
<td>0.13%</td>
<td>&lt;0.1%</td>
<td>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>
<td>0.2%</td>
</tr>
</tbody>
</table>

estimates with "old" near detector location
= conservative
(with new location: $N\nu/2$, $N\nu/3$)

Signal/Bkg >50
Gd-doped Liquid Scintillator

- Stability tests reassuring
  - No change seen over ~700 days
- Scintillator ingredients for both detectors ready to be mixed (MPIK)
- Mixing in one batch
  - Exact proportions for both detectors (H, Gd)

100kg Gd salt
FADC

- Waveform digitisers of νDAQ
  - APC responsibility [Courty, Kryn, Dawson, Akiri]
- Developed in partnership with CAEN
  - V1721X
  - 8 channels
  - digitises at 500 MHz to 8-bit
- Dead-time-less
- Enhanced with In-House firmware
  - Variable waveform size (max 4 μs)
  - 2eSST DMA transfer
- Digitise all PMT signals (60 cards)