Double-Chooz Neutrino Experiment

Carmen Palomares (Ciemat, Spain) for Double-Chooz Collaboration
The main goal of upcoming experiments is the determination of $\theta_{13}$.

**Open questions:**
- Mass hierarchy
- Absolute mass scale
- CP violation effects
- Size of $\theta_{13}$

The main limit comes from CHOOZ reactor experiment '97.

$\theta_{13} < 9.5 \text{ deg}$ @ 90% CL

$\theta_{23} = 45^{+4.4}_{-3.4}$

$|\Delta m_{13}^2| = 2.40 \pm 0.12 \times 10^{-3} \text{ eV}^2$

$\theta_{12} = 33.5^{+1.3}_{-1.0}$

$|\Delta m_{12}^2| = 7.65^{+0.23}_{-0.20} \times 10^{-5} \text{ eV}^2$

@1σ, arXiv:0808.2016
Experimental methods to measure $\theta_{13}$

**Long-Baseline Accelerators:** Appearance ($\nu_\mu \to \nu_e$)
Oscillation probability complicated and dependent not only on $\theta_{13}$ but also:
- CP violation parameter
- Sign of $\Delta m_{31}$
- Size of $\sin^2 \theta_{23}$

**Nuclear reactors:** Disappearance ($\bar{\nu}_e \to \bar{\nu}_e$)
L/E match $\Delta m_{31}^2$ (L~1 Km)
- $\theta_{13}$ independent of CP-violation,
- Weak dependence on $\Delta m_{12}$
- Negligible matter effects.

- Unambiguous measurement of $\Theta_{13}$ complementary to beams
- The only limitation comes from systematic errors
- These experiments must be carried out on a short time scale to provide an input for future beams

\[
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \left(\frac{\Delta m_{21}^2 L}{4E}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}
\]
Neutrino detection at nuclear reactor experiments

Detection by inverse $\beta$-decay

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

Signature $\rightarrow$ Delay coincidence of:

Prompt $e^+$ annihilation $E_{e^+} = E_\nu - (M_n - M_p)$

Photons from $n$ capture on H $E = 2$ MeV

on dedicated nuclei (Gd) $E = 8$ MeV

Using $\beta$ spectra measurements for $^{235}$U, $^{239}$Pu, and $^{241}$Pu can calculate the $\nu_e$ flux to $\sim 1.5\%$. 

From Bemporad, Gratta and Vogel

Observable $\bar{\nu}$ Spectrum

Arbitrary

Flux

Cross Section

On dedicated nuclei (Gd) $E = 8$ MeV
Backgrounds

Accidental:
- $e^+$-like signal: radioactivity from materials and surrounding rock.
- $n$ signal: $n$ from cosmic $\mu$ spallation, thermalized in detector and captured on Gd. Or another radioactivity event

Correlated:
- fast $n$ (by cosmic $\mu$) recoil on $p$ (low energy) and captured on Gd
- long-lived ($^9$Li, $^8$He) $\beta$-decaying isotopes induced by $\mu$
Double Chooz Concept

To look for non-zero values of $\Theta_{13}$

Beyond the previous systematic limitations:

1. **Two detectors** to reduce uncertainties of the reactor flux
2. **Identical detectors** to reduce errors due to detector acceptance

\[ \Delta m^2_{12} = 7.2 \times 10^{-5} \text{ eV}^2; \quad \cos \theta_{12} = 0.8; \quad \sin \theta_{13} = 0.23 \]
\[ \Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2; \quad \Delta m^2_{32} = 2.0 \times 10^{-3} \text{ eV}^2 \]
Improving CHOOZ

CHOOZ: \( R = \frac{N_{\text{meas}}}{N_{\text{exp}}} = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (sys)} \)

### 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 period</td>
<td>Few months</td>
<td>3-5 years</td>
</tr>
<tr>
<td>Event rate</td>
<td>2700</td>
<td>Chooz-far 60000/3y</td>
</tr>
<tr>
<td>Statistical error</td>
<td>2.8%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

### Systematic error

<table>
<thead>
<tr>
<th></th>
<th>CHOOZ</th>
<th>Double Chooz</th>
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</thead>
<tbody>
<tr>
<td>Reactor uncertainties v flux and reactor power</td>
<td>2.1%</td>
<td>----</td>
</tr>
<tr>
<td>Number of protons</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Detector Efficiency</td>
<td>1.5%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
Improving CHOOZ

Background

- **Single e⁺-like** reduced: PMT very low radioactivity glass
  PMT is not in contact with liquid scintillator
  (PMT single rate
  CHOOZ: ~60 Hz. Double-Chooz ~1.5 Hz)
- **Neutron rate** reduced by using a
  more efficient cosmic muon veto system

Detector Performance

- **Calibration** relative detection efficiency between near and far detector
  should be known with an uncertainty <0.5%
- **Detector stability** liquid scintillator stability tested over 3 years
Expected Sensitivity

Current limit @90%CL
\[ \sin^2 2\theta_{13} < 0.11 \]

Limit from Far Chooz (~2010)
\[ \sin^2 2\theta_{13} < 0.06 \]

Limit from Double Chooz (~2012)
\[ \sin^2 2\theta_{13} < 0.035 \]

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

\[ \sigma_{\text{sys}} = 0.6\% \]
The Double Chooz Collaboration

Spokesman: Hervé de Kerret (APC)

**France:** APC Paris, CEA/Dapnia Saclay, Subatech Nantes, Strasburg

**Germany:** Aachen, MPIK Heidelberg, TU München, EKU Tübingen, Hamburg

**Spain:** CIEMAT Madrid

**UK:** Sussex

**Japan:** HIT, Kobe, Niigata, TGU, TIT, TMU, Tohoku

**Russia:** RAS, RRC Kurchatov Institute

**USA:** Alabama, ANL, Chicago, Columbia, Drexel, Illinois, Kansas, LLNL, LSU, Notre Dame, Sandia, Tennessee, UCD

**Brazil:** CBPF, UNICAMP
The Chooz site:

Chooz-B reactors
8.4 GWth
Placed in the Ardennes (France)

Near lab
410 m
115 m.e.w.
500 ν/day

Far lab
1050 m
300 m.e.w.
69 ν/day
The Double Chooz Laboratories

Electronic hut

Glove Box for calibration

Outer veto
The Detector(s)

**Target**: 10.3 m$^3$ Gd doped LS
(Acrylic) $R=1.15m$
$H=2.47m$
$th=8mm$

**y-Catcher**: 22.6 m$^3$ LS
(Acrylic) $R=1.70m$
$H=3.55m$
$th=12mm$

**Buffer**: 114.2 m$^3$ mineral oil
(Stainless Steel) 390 10” PMTs
$R=2.76m$
$H=5.67m$
$th=3mm$

**Inner Veto**: 80 m$^3$ LS
(Steel) 78 8” PMTs
$R=3.27m$
$H=7 m$
$th=10mm$

**Outer muon Veto**
Scintillator panels

**Shielding**: 15 cm Steel
After refurbishment of the pit, the detector construction started in the second half of 2008.
Far Detector Construction

February 2009

Inner Veto PMTs Installation completed
Far Detector Construction

April 2009

Buffer tank assembled on site
Far Detector Construction

May 2009

PMT Installation

Krakow
July 17th 2009
C. Palomares
Double Chooz Experiment
Current Status

PMT Installation completed
Acrylic vessels ready to be assembled on site

July 2009

Krakow
July 17th 2009
Schedule

• Far Detector will be finished at the end of 2009
  Inner Veto and buffer PMT installation in the upper lid
  Electronics

• Filling and commissioning beginning of 2010

• Outer veto will be installed in April 2010
  (not indispensable for running)

From April 2010 a 4 months stop of one of the reactors
(possibility to get a stop of both reactors during some weeks)
May 20th the **agreement for the Near laboratory construction** has been signed. The agreement includes the region Champagne-Ardennes, EDF and French agencies.

**Schedule**
- Geological study done (February)
- Tender process for construction
- Constructed at the end of 2010
Summary

- **Double Chooz** will be the first of a new generation of neutrino experiments using identical detectors at different distances from a reactor to measure $\Theta_{13}$.

- First quarter of 2010 start of data taking with far detector: current limit $\sin^2 2\Theta_{13} < 0.11$ @ 90% CL in few weeks and $< 0.06$ running 1 year.

- 2011 start of data taking with both detectors.

- Detector stability will allow a long data taking period.

- Three years running both detectors: $\sin^2 2\Theta_{13} < 0.03$ @ 90% CL.
Backup
Neutrino oscillations: present status

A non-zero value for $\theta_{13}$?

- Solar + KamLAND data lead to a hint for non-zero $\theta_{13}$ (1.5$\sigma$)
- Therefore, the CHOOZ + atmospheric data give a smaller value.

At present no significant hint for a non-zero $\theta_{13}$

**$\Theta_{13}$ Determination**

$sin^22\Theta_{13} - \delta$ plane for the true values $sin^22\Theta_{13}=0.1$

arXiv:0907.1896

- $\delta=90^{\circ}$
- $\delta=270^{\circ}$

**Combination:**
- Good determination of $\Theta_{13}$
- Some information on $\delta$ (corrupted by the ambiguity in the mass hierarchy)
- CP violation cannot be established

Krakow
July 17th 2009

C. Palomares
Double Chooz Experiment
Determination

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

arXiv:0907.1896
Reactor experiments proposals

G. Mention et al. (in preparation)
Reactor and antineutrino spectrum

Raw reactor data

Power, mass, # fissions
Operation mode (refueling and enrichments)
Monitoring of the power vs time

Reactor evolution code
MURE / DRAGON

Isotope mass
Isotope fission rate

Predicted neutrino spectrum

Neutrino energy spectra of U and Pu
(Simulation code)
## Double-Chooz: Systematic errors

<table>
<thead>
<tr>
<th>Source</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>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 ratio &amp; Gd concentration</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>
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<tr>
<td>Live time</td>
<td>few %</td>
<td>0.25 %</td>
</tr>
<tr>
<td>Analysis</td>
<td></td>
<td></td>
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<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><strong>2.7 %</strong></td>
<td><strong>&lt; 0.6 %</strong></td>
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Two “identical” detectors, Low bkg
Distance measured @ 10 cm + monitor core barycenter
Same weight sensor for both det.
Accurate T control (near/far)
Same scintillator batch + Stability
“identical” Target geometry & LS
Measured with several methods

(1 - 0.45% without contingency ....)
### Background

#### No Veto System

<table>
<thead>
<tr>
<th>Detector</th>
<th>Site</th>
<th>Accidental</th>
<th>Background</th>
<th>Correlated</th>
<th>$^9$Li</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Materials</td>
<td>PMTs</td>
<td>Fast n</td>
<td>$\mu$-Capture</td>
</tr>
<tr>
<td>Double Chooz</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>(69 $\nu$/d)</td>
<td>Far</td>
<td>Rate ($d^{-1}$)</td>
<td>0.5 ± 0.3</td>
<td>1.5 ± 0.8</td>
<td>2.0 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>Near</td>
<td>bkg/$\nu$</td>
<td>0.7%</td>
<td>2.2%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>Rate ($d^{-1}$)</td>
<td>5 ± 3</td>
<td>17 ± 9</td>
<td>9.1 ± 9.1</td>
<td>266</td>
</tr>
<tr>
<td>(500 $\nu$ / d)</td>
<td></td>
<td>bkg/$\nu$</td>
<td>0.5%</td>
<td>1.7%</td>
<td>0.8%</td>
</tr>
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</table>

#### Inner and Outer Veto

<table>
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<tr>
<th>Detector</th>
<th>Site</th>
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<th>Correlated</th>
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</tr>
<tr>
<td>Double Chooz</td>
<td></td>
<td>Rate ($d^{-1}$)</td>
<td>0.1 ± 0.1</td>
<td>0.3 ± 0.2</td>
<td>0.11 ± 0.11</td>
</tr>
<tr>
<td>(69 $\nu$/d)</td>
<td>Far</td>
<td>bkg/$\nu$</td>
<td>0.1%</td>
<td>0.4%</td>
<td>0.2%</td>
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</tr>
<tr>
<td>Double Chooz</td>
<td>Rate ($d^{-1}$)</td>
<td>0.5 ± 0.3</td>
<td>1.7 ± 0.9</td>
<td>0.15 ± 0.15</td>
<td>0.4</td>
</tr>
<tr>
<td>(500 $\nu$ / d)</td>
<td>Near</td>
<td>bkg/$\nu$</td>
<td>&lt; 0.1%</td>
<td>0.2%</td>
<td>&lt; 0.1%</td>
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Calibration System

Deployment of radioactive sources:
Articulated arm (Target)
Guide tubes (Gamma-catcher)
Buffer tubes
Z-axis system

Light Injection:
LED systems IV and buffer
Laser (Z-axis)
Target and G-Catcher

Three targets finished
Cylinder glued
Lid construction: gluing support and filling tube
Target and G-Catcher

**Gamma catcher construction** divided between Néotec site and Chooz power plant to avoid heavy transportation:

- Néotec: Cylinders parts constructed
  Lids constructed and glued

- Chooz: gluing of the cylinder
  gluing of cylinder, lids and filling tubes