Measurement of the neutrino mixing angle $\theta_{13}$ in the Double Chooz experiment

Diana Navas Nicolás
Taller de Altas Energías
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# Neutrino Oscillations

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

**PMNS Matrix**

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

**Atmospheric \( \nu \)**

- \( \sin^2 2\theta_{12} = 0.846 \pm 0.021 \)
- \( \Delta m_{21}^2 = (7.53 \pm 0.18) \cdot 10^{-5} \text{eV}^2 \)
- \( \sin^2 2\theta_{23} = 0.999^{+0.001}_{-0.018} \)
- \( |\Delta m_{31}^2| = (2.43 \pm 0.06) \cdot 10^{-3} \text{eV}^2 \)

**Solar \( \nu \)**

- \( \Delta m_{23}^2 \) sign
- CP \( \delta \) violation

Double Chooz gave the first indication that \( \theta_{13} \neq 0 \)

**Known recently** \( \sin^2 2\theta_{13} = 0.084 \pm 0.005 \)
Nuclear Reactor Neutrinos

$\bar{\nu}_e$ disappearance is directly related with $\theta_{13}$

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

- Univocal determination of $\theta_{13}$
  - No dependence with $\delta_{CP}$
  - No dependence with mass hierarchy

- Reactor advantages
  - There is no matter effect
  - Pure $\bar{\nu}_e$ beam
  - High flux of low energy

$E_\nu = 3$ MeV

Oscillation parameters from PDG 2014
Double Chooz Experiment

Chooz, Francia

120 mwe
~300 ν/day
December 2014
400 m

300 mwe
~40 v/day
April 2011
1 km

<table>
<thead>
<tr>
<th>Distance</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 m</td>
<td>~300 ν/day</td>
</tr>
<tr>
<td>1 km</td>
<td>~40 ν/day</td>
</tr>
</tbody>
</table>

\[
\sin^2 \theta_{13} \approx \frac{1}{1/\Delta m_{31}^2}
\]

\[
\sin^2 \theta_{12} \approx \frac{1}{\Delta m_{21}^2}
\]
Multi-detectors analysis

FD-I (single detector) 461 days
+ FD-II (multi-detectors) 212 days

ND (multi-detectors) 151 days

Reactor flux error highly suppressed with multi-detectors
**Inverse $\beta$ decay**

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

- **Prompt signal:** Energy loses $+ e^+$ anihilation
  \[ E(e^+) \approx E(\bar{\nu}_e) - 0.8 \text{ MeV} \]
- **Delayed signal:** Neutron capture on Gadolium (Gd)
  \[ 8 \text{ MeV } \gamma \text{ rays} \]
- Alternaly, neutron capture on Hidrogen (H) ($\sim 2.2 \text{ MeV}$)
Double Chooz detector

Outer Veto
Plastic scintillation strips

ν – Target
10.3 m³ Gd-loaded liquid scintillator

‘Y - Catcher
22.5 m³ Gd-free liquid scintillator

Buffer
110 m³ non-scintillating mineral oil layer. 390 10’’ PMTs

Inner Veto
90 m³ thick liquid scintillator layer. 78 8’’ PMTs

Steel shield (FD)
Water shield (ND)
IBD candidates selection

• Preselection
  1. Valid trigger (E\geq 0.4 \text{ MeV})
  2. Muon veto (Event is a muon if E_{IV} > 16\text{MeV} \text{ or } E_{ID} > 20\text{MeV})
  3. Rejection of the events subsequent to a $\mu$ ($\Delta t > 1000 \mu s$ [Gd], $\Delta t > 1250 \mu s$ [H])
  4. Rejection of light noise (LN) signals produced in the PMT basis

• Selection

<table>
<thead>
<tr>
<th></th>
<th>Análisis de Gd</th>
<th>Análisis de H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation</td>
<td>[-200,600] \mu s</td>
<td>[-800,900] \mu s</td>
</tr>
<tr>
<td>Prompt energy</td>
<td>0.5&lt;E_{vis}&lt;20 \text{MeV}</td>
<td>1.0&lt;E_{vis}&lt;20 \text{MeV}</td>
</tr>
<tr>
<td>Delayed energy</td>
<td>4.0&lt;E_{vis}&lt;10 \text{MeV}</td>
<td>1.3&lt;E_{vis}&lt;3 \text{MeV}</td>
</tr>
<tr>
<td>Temporal coincidence</td>
<td>0.5&lt;\Delta t&lt;150 \mu s</td>
<td>0.5&lt;\Delta t&lt;800 \mu s</td>
</tr>
<tr>
<td>Distance coincidence</td>
<td>$\Delta R&lt;100\text{cm}$</td>
<td>$\Delta R&lt;120\text{cm}$</td>
</tr>
<tr>
<td>ANN</td>
<td>-</td>
<td>&gt; -0.23</td>
</tr>
</tbody>
</table>
IBD selection

Good data: MC agreement!

Observed IBD rate: ~40 d$^{-1}$ (FD) and ~300 d$^{-1}$ (ND)

Remaining BG are:
- Accidental coincidence: e.g.) environmental $\gamma$ + spallation neutrons $n$
- Fast neutron: $n + p \rightarrow$ recoil $p + n$
- Stopping muon: $\mu \rightarrow e + \nu + \nu$
- ($\beta$, $n$) emitter from spallation products: e.g.) $^9\text{Li} \rightarrow ^8\text{Be} + e + \nu + n$

( ) : prompt (delayed) signal
Neutrino detection efficiency

To estimate the value of $\theta_{13}$ two different analyses are applied

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Being

$$N(E)_{\text{Observed}} = [\varepsilon_{\text{tot}} \times N(E)_{\text{Exp}} + N(E)_{\text{BG}}]$$

Observed neutrino candidates

Neutrino detection efficiency

Expected neutrino flux

Background

The detection efficiency is defined as

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{prompt}} \times \varepsilon_{\text{delay}} \times \varepsilon_{\text{vetoes}} \times \varepsilon_{\text{proton#}}$$

$$\varepsilon_{\text{delay}} = \varepsilon_{\text{n-captures}} \times \varepsilon_{\text{cut}} \times \varepsilon_{\text{spill}}$$

Efficiency correction ratios

$$c_\zeta = \frac{\varepsilon_{\text{DATA FD}}}{\varepsilon_{\text{DATA ND}}} \text{ or } \frac{\varepsilon_{\text{DATA}}}{\varepsilon_{\text{MC}}}$$

with $\zeta=$ each contribution of $\varepsilon_{\text{delay}}$
Neutron Sources

IBD neutrons

- Homogeneously distributed within the detector.
- Same neutron physics and event selection as the oscillation signal.

Cf-source neutrons

- Point-like fission source emitting $\sim 10$ n/s. Deployed at specific locations within the detector.
- Selected using delayed coincidence: prompt: fission $\gamma$; delayed: neutron captures.
$\varepsilon_{\text{delay}} = \varepsilon_{n\text--\text{captures}} \times \varepsilon_{\text{cut}} \times \varepsilon_{\text{spill}}$

Neutrons can be captured on Gd, H or C nuclei.

$\varepsilon_{n\text--\text{captures}} = \frac{N_{\text{Gd}}}{N_{\text{Gd}} + N_{\text{H}}}$

Number of Gd capture events

Number of H capture events

The $\varepsilon_{n\text--\text{captures}}$ allow to study the fraction of n-captures on Gd and to estimate the concentration of Gd in the $\nu$target liquid scintillator.

$N_{\text{Gd}} = N(3.5 < E_{\text{vis}} < 10 \text{ MeV})$

$N_{\text{H}} = N(1.3 < E_{\text{vis}} < 3.5 \text{ MeV})$

Efficiency fractions at target center to be introduced in $\theta_{13}$ fit:

$c_0 = \frac{\varepsilon_{n\text--\text{captures}}}{\varepsilon_{n\text--\text{captures}}} \frac{\text{DATA ND}}{\text{DATA FD}}$ or $\frac{\varepsilon_{n\text--\text{captures}}}{\varepsilon_{n\text--\text{captures}}} \frac{\text{DATA}}{\text{MC}}$
Volume-wide detection (I)

\[ \varepsilon_{\text{delay}} = \varepsilon_{\text{n-captures}} \times \varepsilon_{\text{cut}} \times \varepsilon_{\text{spill}} \]

- The \( \varepsilon_{\text{cut}} \) studies the **impact of the neutrino selection criteria**.
- Efficiency definition including the selection cuts.
- Only non-neutron delayed events are background (BG). Accidental BG is subtracted using an off-time selection.

### IBD cut efficiency definition

- **Number of IBD candidates**
  \[ \varepsilon_{\text{cut}} = \frac{N(\text{4} < E_n < 10 \text{ MeV} \cap 0.5 < \Delta t < 150 \mu \text{s} \cap \Delta R < 1 \text{m})}{N(3.5 < E_n < 10 \text{ MeV} \cap 0.5 < \Delta t < 800 \mu \text{s} \cap 0 < \Delta R < 1.2 \text{m})} \]

- **Number of Gd capture events**

- **Candidate isolation cuts**

- **Efficiency fractions in the detector volume to be introduced in \( \theta_{13} \) fit.**

\[ c_v = \frac{\varepsilon_{\text{cut DATA FD}}}{\varepsilon_{\text{cut DATA ND}}} \text{ OR } \frac{\varepsilon_{\text{cut DATA}}}{\varepsilon_{\text{cut MC}}} \]
Volume-wide detection (II)

\[ \varepsilon_{\text{delay}} = \varepsilon_{n-\text{captures}} \times \varepsilon_{\text{cut}} \times \varepsilon_{\text{spill}} \]

▲ Near detector efficiency map for 15 months of ND DATA (Left plot) and for a ND MC (Right plot). White dotted lines delimit target, gamma catcher and buffer volumes.
Neutron migration

\[ \varepsilon_{\text{delay}} = \varepsilon_{n-\text{captures}} \times \varepsilon_{\text{cut}} \times \varepsilon_{\text{spill}} \]

- **\( \nu \text{Target} \)** constitutes the **fiducial volumen** in which the occurring IBD events are selected.
- Due to **neutron migrations** between **\( \nu \text{Target} \)** and **\( \gamma \text{-catcher} \)** volumes, the **IBDs can be captured in either volumes**.

Estimated by the **comparison of two MC**: Double Chooz MC (Geant4 + custom thermalization based on an analytical model) vs Tripoli-4 (neutron transport code developed for reactor physics based on experimental nuclear data).
## Summary detection systematics

**Double Chooz Preliminary**

<table>
<thead>
<tr>
<th></th>
<th>FD-I</th>
<th>FD-II</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG vetoes (%)</td>
<td>0.11 (0.11)</td>
<td>0.09 (0.09)</td>
<td>0.02 (0.02)</td>
</tr>
<tr>
<td>Gd fraction (%)</td>
<td>0.25 (0.14)</td>
<td>0.26 (0.15)</td>
<td>0.28 (0.19)</td>
</tr>
<tr>
<td>IBD selection (%)</td>
<td>0.21 (0.21)</td>
<td>0.16 (0.16)</td>
<td>0.07 (0.07)</td>
</tr>
<tr>
<td>Spill in/out (%)</td>
<td>0.27 (0)</td>
<td>0.27 (0)</td>
<td>0.27 (0)</td>
</tr>
<tr>
<td>Proton number (%)</td>
<td>0.30 (0)</td>
<td>0.30 (0)</td>
<td>0.30 (0)</td>
</tr>
<tr>
<td><strong>Total (%)</strong></td>
<td><strong>0.49 (0.26)</strong></td>
<td><strong>0.47 (0.22)</strong></td>
<td><strong>0.38 (0.15)</strong></td>
</tr>
</tbody>
</table>

Numbers in parentheses are uncorrelated uncertainties in multi-detectors analysis (FD-I, FD-II and ND)

Neutron detection efficiency uncertainty:
- 0.34% for FD-I (previous analysis FD-I 0.53%)
- 0.41% for FD-II and 0.40 % for ND
Multidetector fit results

- **Best-fit**: \(\sin^2 2\theta_{13} = 0.111 \pm 0.018\) (stat. + syst.) \((\chi^2/\text{dof} = 128.8/120)\)

- **Non-zero** \(\theta_{13}\) observation at 5.8\(\sigma\) C.L.

- **Spectral distortion** between 4 – 6 MeV.
  - Scales with reactor power.
  - Also observed in the Daya Bay and RENO experiments.
  - Unaccounted \(\bar{\nu}_e\) component in the reactor flux model.
  - Out of the oscillation range. \(\theta_{13}\) unaffected.
Expected Future Improvements

Current analysis (Gd-only) is statistically limited
→ Inclusion of H-capture event (Gd+H analysis!)
Improve statistics by almost factor 3!
Conclusions

• Double Chooz is taking data with 2 detectors since beginning of 2015

• Preliminary result: $\sin^2(2\theta_{13}) = 0.111 \pm 0.018$ (stat.+syst.) (Previous analysis: $\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$)
  - Reactor flux uncertainty strongly suppressed to < 0.1%
  - Other systematic uncertainties ≤ 0.5%

• Completely new analysis since Moriond 2016 (Gd+H) in progress ⇒ Update results soon
  - Improved statistics. Since March 2016: 5x more statistics in 3 months
  - New result with improved sensitivity!
Thank you!
Back-up
Double Chooz Collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP, SPbN
SEDI, SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC

Germany
EKU
Tübingen
MPIK
Heidelberg
RWTH
Aachen
TU München

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

USA
U. Alabama
ANL, U.
Chicago
Columbia U.
UC Davis
Drexel U.
IIT, KSU, MIT,
U. Notre Dame
U. Tennessee
Virginia Tech
Uncertainties in multi-detectors analysis

- Systematic errors suppressed with two detectors and in rate+shape fit
  ⇒ All systematic uncertainties below < 0.4\% (after R+S fit)
- Current precision (9 months ND) is limited by the statistical uncertainty

**Notes**:
- SD: single detector
- MD: relative uncertainties in multiple detectors

**Graph Details**:
- **Signal statistics**
- **Reactor flux (SD)**
- **Reactor flux (MD)**
- **FD-I – FD-II relative**
- **Detection & E (SD)**
- **Detection & E (MD)**
- **Background**
- **BG (after R+S fit)**

**References**:
- *JHEP* 1410 (2014) 086
- Moriond Preliminary
Double Chooz $\theta_{13}$ in the world

- DC $\theta_{13}$ is higher than other reactor $\theta_{13}$ by $\sim 30\%$ (1.4$\sigma$ wrt Daya Bay)
- Long baseline (T2K, NOvA) weakly favors higher $\theta_{13}$ than reactor average
- Reactor $\theta_{13}$ is key parameter to solve CP-violation and mass hierarchy