Latest results of the Double Chooz reactor neutrino experiment

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Neutrino oscillation

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix} \neq \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

flavour eigenstates

mass eigenstates
Neutrino oscillation

**PMNS mixing matrix**
(Pontecorvo Maki Nakagawa Sakata)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Oscillation probability of a neutrino \(\nu_\alpha\) with energy \(E\) after a distance \(L\):

\[
P_{\nu_\alpha \rightarrow \nu_\beta} \approx \sin^2\left(2\theta_{ij}\right)\sin^2\left(\Delta m^2_{ij}L/4E\right)
\]

\(\Delta m^2_{ij} = m^2_i - m^2_j\)
Neutrino oscillation

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PMNS matrix is unitary: reduction of parameters to 3 mixing angles + 1 phase
Neutrino oscillation

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PMNS matrix is unitary: reduction of parameters to 3 mixing angles + 1 phase

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos\theta_{23} & \sin\theta_{23} \\
0 & -\sin\theta_{23} & \cos\theta_{23}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
\begin{pmatrix}
\nu_\alpha \\
\nu_\beta
\end{pmatrix} =
\begin{pmatrix}
\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos\theta_{12} & \sin\theta_{12} & 0 \\
-\sin\theta_{12} & \cos\theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\delta: \text{neutrino/antineutrino asymmetry (CP violation)}\]
Neutrino oscillation

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\nu_3
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\]

Oscillation experiments optimised to study mixing between two states :

\[
\begin{pmatrix}
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\end{pmatrix} =
\begin{pmatrix}
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\end{pmatrix}
\begin{pmatrix}
\nu_i \\
\nu_j
\end{pmatrix}
\]

Oscillation probability of a neutrino \( \nu_\alpha \) with energy \( E \) after a distance \( L \) :

\[
P_{\nu_\alpha \to \nu_\beta} \approx \sin^2(2\theta_{ij}) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) \quad \text{avec} \quad \Delta m_{ij}^2 = m_i^2 - m_j^2
\]
Reactor neutrino oscillation and $\theta_{13}$ measurement

nuclear reactor = point-like, intense ($\sim 10^{21} \nu$/GWth) and free source of pure $\bar{\nu}_e$

Survival probability

$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$

- $\theta_{13}$ last unknown parameter until 2012
- measurement through disappearance of $\bar{\nu}_e$ in a far detector (at $\approx 1$ km)
- identical near detector for high precision (reduce detection+flux errors)
Reactor neutrino oscillation and $\theta_{13}$ measurement

A nuclear reactor is point-like, intense ($\sim 10^{21} \, \nu / \text{GWth}$) and a free source of pure $\bar{\nu}_e$.

Survival probability $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$

- $1/\Delta m^2_{31}$
- $\sin^2 \theta_{13}$
- $\approx 1/\Delta m^2_{21}$

- $\theta_{13}$ last unknown parameter until 2012
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Survival probability $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$

$1/\Delta m^2_{31}$

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$\approx 1/\Delta m^2_{21}$

$\sin^2 \theta_{12}$

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Double Chooz international collaboration

150 physicists/engineers from 7 countries

Spokesperson : Hervé de Kerret (CNRS/IN2P3)
Project Manager : Christian Veyssière (CEA Saclay)
Double Chooz experiment layout

CNPE Chooz
2x N4 reactors
(4.25 GWth)

NEAR DETECTOR
since January 2015

FAR DETECTOR
since April 2011

120 mwe
400 m
1050 m
300 mwe
Double Chooz experiment layout

CNPE Chooz
2x N4 reactors
(4.25 GWth)

FAR DETECTOR
since april 2011

NEAR DETECTOR
since january 2015

~ $10^{25}$ ν / day
from the 2 reactors

120 mwe
400 m
1050 m
300 mwe
Double Chooz experiment layout

- **CNPE Chooz**
  - 2x N4 reactors
  - (4.25 GWth)

- **NEAR DETECTOR**
  - since January 2015

- **FAR DETECTOR**
  - since April 2011

- ~ $10^{25}$ ν / day from the 2 reactors
- near detector ~ 300 ν / day
- far detector ~ 40 ν / day

120 mwe

400 m

1050 m

300 mwe
Double Chooz experiment layout

CNPE Chooz
2x N4 reactors
(4.25 GWth)

NEAR DETECTOR
since January 2015

FAR DETECTOR
since April 2011

~ \(10^{25} \text{ v/day}\) from the 2 reactors

near detector
~ 300 v/day

far detector
~ 36 v/day

120 mwe
400 m
1050 m
300 mwe
Double Chooz detector

9 m

7 m

9 m

7 m
Double Chooz detector

Neutrino target
liquid scintillator
with Gd (8 tons)
Double Chooz detector

Neutrino target
liquid scintillator with Gd (8 tons)

Gamma catcher
liquid scintillator without Gd
Double Chooz detector

- **Neutrino target**: liquid scintillator with Gd (8 tons)
- **Gamma catcher**: liquid scintillator without Gd
- **Buffer**: mineral oil 390x 10" PMTs
Double Chooz detector

- **Neutrino target**: liquid scintillator with Gd (8 tons)
- **Gamma catcher**: liquid scintillator without Gd
- **Buffer**: mineral oil
  - 390x 10" PMTs
- **Inner Veto**: liquid scintillator
  - 78x 8" PMTs
Detection principle

“IBD” (Inverse Beta Decay)

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

**Prompt signal**: positron

\[ E_{\text{prompt}} \approx E(\nu_e) - 0.78 \text{ MeV} \]

**Delayed signal**: radiative neutron capture

- Gd capture
  \[ E \approx 8 \text{ MeV} \]
  \[ \Delta T \approx 30 \mu\text{s} \]
- H capture
  \[ E \approx 2.2 \text{ MeV} \]
  \[ \Delta T \approx 150 \mu\text{s} \]
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<table>
<thead>
<tr>
<th>Capture</th>
<th>Energy (MeV)</th>
<th>Time Delay (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>H</td>
<td>2.2</td>
<td>150</td>
</tr>
</tbody>
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OR
Detection principle

“IBD” (Inverse Beta Decay)

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

**prompt signal**: positron  
\[ E_{\text{prompt}} \approx E(\nu_e) - 0.78 \text{ MeV} \]

**delayed signal**: radiative neutron capture

Visible Energy (MeV)  
2 4 6 8 10

**REACTOR NEUTRINO SPECTRUM**  
**INTERACTION CROSS SECTION**  
**DETECTED SPECTRUM**
Background components

Cosmogenetic β-n emitter (mainly $^9$Li)

Correlated fast-neutrons, stopping muons

Accidentals natural radioactivity ($^{208}$Tl, $^{40}$K, ...)

Neutrino signal

Visible Energy (MeV)
Background components

**Background Spectrum**

- **Neutrino signal**
- **Cosmogenetic**
- **Correlated**
- **Accidentals**

**Legend**

- **β**-n emitter (mainly \(^9\)Li)
- Stopping-μ
- Michel electrons
- Fast-neutrons, stopping muons
- Natural radioactivity (\(^{208}\)Tl, \(^{40}\)K, ...)

**Graph**

Visible Energy (MeV) vs. Background Spectrum (Arbitrary Unit)

⇒ Rate + shape information (from data) are exploited in oscillation fit.
Background components

- **μ\(_n\)-Gd/H\(_p\)-recoil** stopping-μ \(\rightarrow\) Michel e\(^{-}\) correlated fast-neutrons, stopping muons
- **cosmogenetic** β-n emitter (mainly \(^9\)Li)
- **correlated** natural radioactivity \((^{208}\text{Tl}, ^{40}\text{K}, ...\))
- **accidentals**

The graph shows the background spectrum with an arbitrary unit on the vertical axis and visible energy in MeV on the horizontal axis. The categories include:
- **Neutrino signal**
- **Cosmogenetic**
- **Correlated**
- **Accidentals**

The rate and shape information from the data are exploited in the oscillation fit.
Background components

- **cosmogenetic**
  - β-n emitter (mainly $^9\text{Li}$)

- **correlated**
  - fast-neutrons, stopping muons

- **accidentals**
  - natural radioactivity ($^{208}\text{TI}, ^{40}\text{K}, ...$)

Visible Energy (MeV)

BACKGROUND SPECTRUM (ARBITRARY UNIT)

- **neutrino signal**
- **cosmogenetic**
- **correlated**
- **accidentals**

The rate and shape information (from data) are exploited in oscillation fit.
Background components

Visible Energy (MeV)

BACKGROUND SPECTRUM (ARBITRARY UNIT)

- **neutrino signal**
- **cosmogenic**
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- **cosmogenic**
  - $\beta$-n emitter
  - (mainly $^9\text{Li}$)

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  - fast-neutrons, stopping muons

- **accidentals**
  - natural radioactivity
  - ($^{208}\text{Tl}$, $^{40}\text{K}$, ...)

$\Rightarrow$ rate+shape information (from data) are exploited in oscillation fit
Double Chooz’ Single-Detector phase

- SD phase with only far detector (FD-I)
- Bugey4 used as anchor of flux (1.4 % precision)

- 1st publication on spectrum distortion [JHEP 1410 (2014) 86]
Double Chooz’ Single-Detector phase

- SD phase with only far detector (FD-I)
- Bugey4 used as anchor of flux (1.4 % precision)

- indication of non-zero $\theta_{13}$
- 1st n-H capture analysis
- 1st reactor rate modulation analysis
- 1st publication on spectrum distortion

[JHEP 1410 (2014) 86]
Double Chooz’ Multiple-Detector phase

- MD phase with far detector (FD-II) and near detector (ND)
- **identical detectors** cancels correlated errors (ex: detection efficiency)
- **nearly iso-flux** configuration: flux error $\sim 0.1\%$
Increased stats Gd+H

statistics is limiting factor for about 10 years @ Double Chooz
⇒ new strategy: enlarge effective volume by Gd+H analysis

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<tr>
<th>IBD rate</th>
<th>Gd analysis</th>
<th>Gd+H analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD</td>
<td>$\sim40;d^{-1}$</td>
<td>$\sim100;d^{-1}$</td>
</tr>
<tr>
<td>ND</td>
<td>$\sim300;d^{-1}$</td>
<td>$\sim800;d^{-1}$</td>
</tr>
</tbody>
</table>

$\sim2.5\;times$
Increased stats Gd+H

statistics is limiting factor for about 10 years @ Double Chooz
⇒ new strategy: enlarge effective volume by Gd+H analysis

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</tr>
<tr>
<td>ND</td>
<td>~300 d⁻¹</td>
<td>~800 d⁻¹</td>
</tr>
</tbody>
</table>

~2.5 times

challenge of Gd+H analysis: accidental background, detection efficiency
Accidental background rejection with ANN

Artificial Neutral Network (ANN) based on 3 observables

Delayed signal energy

Correlation time

Correlation distance

Double Chooz Preliminary
IBD (Gd+H)
Accidental background rejection with ANN

Artificial Neutral Network (ANN) based on 3 observables

Before ANN

- Delayed signal energy
- Correlation time
- Correlation distance

After ANN

- Delayed signal energy
- Correlation time
- Correlation distance

unprecedented accidentals reduction $\rightarrow$ negligible impact on $\theta_{13}$ measurement
Prompt energy spectra

FD-I
\sim 40k \text{ IBD}

FD-II
\sim 40k \text{ IBD}

ND
\sim 200k \text{ IBD}
simultaneous $\chi^2$ fit DATA/MC for each data set

$\sin^2 2\theta_{13} = 0.119 \pm 0.016 \quad (\chi^2/\text{NDF} = 236.2/114)$
Fit results

simultaneous $\chi^2$ fit DATA/MC for each data set

$\sin^2 2\theta_{13} = 0.119 \pm 0.016$  \hspace{1em} ($\chi^2$/NDF = 236.2/114)

<table>
<thead>
<tr>
<th>background</th>
<th>FD estimation</th>
<th>FD fit output</th>
<th>ND estimation</th>
<th>ND fit output</th>
</tr>
</thead>
<tbody>
<tr>
<td>cosmogenic ($^9$Li)</td>
<td>2.59 $\pm$ 0.61</td>
<td>2.55 $\pm$ 0.23</td>
<td>11.1 $\pm$ 3.0</td>
<td>14.4 $\pm$ 1.2</td>
</tr>
<tr>
<td>correlated (fast-n)</td>
<td>2.54 $\pm$ 0.10</td>
<td>2.51 $\pm$ 0.05</td>
<td>20.8 $\pm$ 0.4</td>
<td>20.9 $\pm$ 0.3</td>
</tr>
</tbody>
</table>
$\sin^2 2\theta_{13} = 0.123 \pm 0.023$ \hspace{1em} ($\chi^2$/NDF = 10.6/38)

data/MC fit : 0.119 $\pm$ 0.016 \hspace{1em} ($\chi^2$/NDF = 236.2/114)

spectral distortion is well cancelled with data/data ratio
Conclusions and prospects

- **SD phase (2011–2014)**: reactor flux error dominant
- **MD phase (2015–2018)**: improved statistics (Gd+H) and flux error suppressed
- **Current result**: \( \sin^2 2\theta_{13} = 0.119 \pm 0.016 \) (latest Daya Bay: \( 0.084 \pm 0.003 \))
- Largest systematic from detection (proton number uncertainty)
  → work in progress to reach a precision \( \leq 0.01 \)

**Reactor \( \theta_{13} \) will be key parameter to solve CP in lepton sector**
THANK YOU FOR YOUR ATTENTION