Latest results of the Double Chooz reactor neutrino experiment

Matthieu Vivier
on behalf the Double Chooz collaboration

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Rencontres du Vietnam 2017, Quy Nhon
The Double Chooz site

Running since April 2011
Overburden ≈300 mwe

Running since Dec. 2014
Overburden ≈120 mwe

400 m

1050 m

2 N4-type PWRs reactors
4.25 GWth each (~10^{21} v_e/s)

CEA/DSM/IRFU - DCom/L.COBEL
Double Chooz collaboration

150 scientists from 7 countries
Spokesperson: Hervé de Kerret (CNRS/IN2P3)
Project manager: Christian Veyssièreme (CEA Saclay)
Detection of antineutrinos

- Detection of antineutrinos through inverse beta decay (IBD) reaction:

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

- **Prompt** $e^+$ energy deposition:
  - Ionization + $e^+/e^-$ annihilation
  - \( E_{\text{vis}} \approx E(\nu_e) - 0.782 \text{ MeV} \)

- **Delayed** energy deposition:
  - 8 MeV (resp. 2.2 MeV) $\gamma$-ray cascade from neutron capture on Gd (resp. H)

- **Time/space correlation:**
  - n-Gd: \( \Delta t \approx 30 \mu s \)
  - n-H: \( \Delta t \approx 200 \mu s \)

- Threshold reaction: \( E_\nu \geq 1.8 \text{ MeV} \)
- Relatively high cross-section \( (\sigma_{\text{IBD}} \approx 10^{-42} E_\nu^2 \text{ cm}^2) \) compared to other detection channels
- Time/space coincidence between $e^+$ and neutron signal allows a strong suppression of backgrounds
Backgrounds

Accidental coincidences

Random coincidences between prompt-like & delayed-like energy depositions:

- Prompt: gammas from radioactivity in surrounding materials & rock
- Delay: neutrons from cosmic muons spallation, β decay of cosmogenic isotopes

Correlated events

Muon-induced fast neutrons and stopping muons:

- Prompt: recoil proton from fast neutron scattering or muon track
- Delay: neutron capture or Michel e⁻

Cosmogenic isotopes

β-n emitters produced by muon spallation (⁹Li or ⁸He):

- Prompt: β particle
- Delay: neutron capture
Double Chooz detectors

A concentric arrangement of cylindrical sub-detectors...
Double Chooz detectors

A concentric arrangement of cylindrical sub-detectors...

**µ vetoes**

- **Outer µ veto**: plastic scintillator strips
- **Inner µ veto**: 90 m$^3$ of LAB scintillator (50 cm thick) in a stainless steel tank equipped with 78 8’ PMTs
Double Chooz detectors

A concentric arrangement of cylindrical sub-detectors...

**μ vetoes**

- **Outer μ veto**: plastic scintillator strips
- **Inner μ veto**: 90 m$^3$ of LAB scintillator (50 cm thick) in a stainless steel tank equipped with 78 8’ PMTs

**Inner detector (IV)**

- **Buffer volume**: 100 m$^3$ of transparent mineral oil (105 cm thick) in a stainless steel tank, equipped with 390 low background 10’ PMTs
- **γ catcher**: 55 cm thick Gd-free LS (PXE) layer contained in a transparent acrylic vessel
- **ν target**: 10 m$^3$ of Gd-doped LS (PXE + 1 g/L of Gd)

+ central chimney connected to all layers for calibration source insertion
+ fast readout electronics
+ laser system for PMT gain calibration
+ etc ...
Double Chooz configurations

- Two reactors & two detectors
- DC unique features:
  - Nearly isoflux configuration: relative v flux uncertainties between ND & FD are almost entirely cancelled
  - 7 days of reactor OFF data

- Two phases:
  - Single-detector (SD): ~ 480 days (FD-I only)
  - Multiple-detector (MD): ~ 350 days (FD-II +ND)

- Bugey-4 anchor: Bugey-4 experimental result is used as a virtual ND
Single-detector analysis

DC-II dataset (2012)

DC-III dataset (2013)

<table>
<thead>
<tr>
<th></th>
<th>n-Gd</th>
<th>Reactor ON</th>
<th>Reactor OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live-time (days)</td>
<td>460.67</td>
<td>7.24</td>
<td></td>
</tr>
<tr>
<td>Neutrino candidates</td>
<td>17351</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Total prediction* (bck included)</td>
<td>$18290^{+370}_{-330}$</td>
<td>$12.9^{+3.1}_{-1.4}$</td>
<td></td>
</tr>
</tbody>
</table>

* Neutrino oscillation not included in the prediction

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Two neutrino detection channels

Gadolinium analysis
- Standard analysis
- High cross-section for neutron capture
- Low (accidental) background

Hydrogen analysis
- Factor 2 more statistics (include GC volume)
- Different systematics & backgrounds
- High (accidental) background

<table>
<thead>
<tr>
<th>DC-III</th>
<th>Gd analysis</th>
<th>H analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon veto</td>
<td>$\Delta t &gt; 1 \text{ ms}$</td>
<td>$\Delta t &gt; 1.25 \text{ ms}$</td>
</tr>
<tr>
<td>Light noise rejection</td>
<td>$Q_{\text{max}}/Q_{\text{tot}}$ &amp; RMS($Q_{\text{start}}$) conditions</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{prompt}}$</td>
<td>0.5 – 20.0 MeV</td>
<td>1.0 – 20.0 MeV</td>
</tr>
<tr>
<td>$E_{\text{delayed}}$</td>
<td>4.0 – 10.0 MeV</td>
<td>1.3 – 3.0 MeV</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>0.5 – 150 $\mu$s</td>
<td>0.5 – 800 $\mu$s</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>&lt; 1 m</td>
<td>&lt; 1.2 m</td>
</tr>
<tr>
<td>ANN</td>
<td>-</td>
<td>$\geq -0.23$</td>
</tr>
<tr>
<td>Multiplicity</td>
<td>No additional trigger around signal</td>
<td></td>
</tr>
<tr>
<td>Vetoes</td>
<td>OV veto, FV veto, Li veto, IV veto</td>
<td></td>
</tr>
<tr>
<td>Signal/Bck</td>
<td>$\sim 23$</td>
<td>$\sim 10$</td>
</tr>
</tbody>
</table>

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Two neutrino detection channels

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Complementary analyses

Gd

H

JHEP 1410 (2014) 086

JHEP 1601 (2016) 163
Gadolinium analysis

**Rate + shape fit to n-Gd IBD spectrum**

- Background-subtracted data
- No oscillation
- Systematic uncertainty
- Best fit: \( \sin^2 2\theta_{13} = 0.090 \)
  at \( \Delta m^2 = 0.00244 \text{ eV}^2 \)

DC-III (n-Gd) Preliminary
Livetime: 467.90 days

\[
\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029} \text{ (stat. + syst.)}
\]
\[
\chi^2_{\text{min}} / n_{\text{dof}} = 52.2 / 40
\]

Hydrogen analysis

**Rate + shape fit to n-H IBD spectrum**

- Data
- No-oscillation signal
- Accidents
- Fast n + stopping μ
- \( ^{3}\text{Li} + ^{3}\text{He} \)

DC-III (n-H), Livetime = 462.72 days

\[
\sin^2(2\theta_{13}) = 0.124^{+0.030}_{-0.039} \text{ (stat. + syst.)}
\]
\[
\chi^2_{\text{min}} / n_{\text{dof}} = 69.4 / 38
\]

JHEP 1410 (2014) 086

JHEP 1601 (2016) 163

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Gadolinium analysis

Rate + shape fit to n-Gd spectrum

\[ \sin^2(2\theta_{13}) = 0.088^{+0.033}_{-0.039} \text{ (stat. + syst.)} \]

\[ \chi^2_{\text{min}}/n_{\text{dof}} = 52.2/40 \]

JHEP 1410 (2014) 086

Hydrogen analysis

Reactor rate modulation analysis

Rate + shape fit to n-H spectrum

\[ \sin^2(2\theta_{13}) = 0.124^{+0.030}_{-0.039} \text{ (stat. + syst.)} \]

\[ \chi^2_{\text{min}}/n_{\text{dof}} = 69.4/38 \]

JHEP 1601 (2016) 163
■ Spectral distortion observed in the 4-6 MeV region (3σ deviation w.r.t. reactor predictions)

■ Several cross-checks have shown:
  o $\theta_{13}$ not affected by the distortion
  o No correlation with backgrounds
  o Strong correlation with reactor power

■ Observed by other reactor experiments
First indication of reactor neutrino disappearance (non-zero $\theta_{13}$), 101 days


First measurement of $\theta_{13}$ using neutron capture on H, 240.1 days


Direct measurement of backgrounds using reactor OFF data

*Phys. Rev. D 87 (2013) 0111012R*

Novel backgrounds reduction techniques & observation of spectral distortion at 4-6 MeV

*JHEP 1601 (2016) 163*

Various measurements of $\theta_{13}$ with the far detector:


- High purity IBD selection

- Well understood systematics at the per mil level (detection, energy & backgrounds)

- Bugey-4 as an anchor for reactor flux normalization
First multi-detector data

- ND running since Dec. 2014
- Live time:
  - FD-I + FD-II: 673.14 days
  - ND: 150.76 days
- MD results presented for the 1st time at Moriond 2016
“Enlarging” the neutrino target...

IBD n-Gd

IBD n-(Gd+H)

Total target \( \sim 8 \) t:
the smallest \( \theta_{13} \) single neutrino target...

Total target \( \sim 26 \) t:
the largest \( \theta_{13} \) single neutrino target...

Statistics enhanced by almost a factor 3...
IBD candidate selection

Far Detector

Near Detector

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The new IBD candidate selection integrates over all captures inclusively: cuts wide open!
- The 8 MeV n-Gd capture associated events have low background contamination
- The 2.2 MeV n-H capture events are highly contaminated by accidental background

New analysis technique developed: **Artificial Neural Network analysis**
- Highly efficient IBD selection in the full delayed energy range
- Efficient background discrimination, especially in the n-H peak region

Evaluating systematic uncertainties from this new analysis scheme is challenging
ANN construction

- ANN cut definition based upon 3 variables
  - $E$ (delay)
  - $\Delta t$ (prompt-delay)
  - $\Delta R$ (prompt-delay)

- Training with accurate MC for IBD signal and data for accidental background
- ANN cut definition based upon 3 variables
  - $E$ (delay)
  - $\Delta t$ (prompt-delay)
  - $\Delta R$ (prompt-delay)

- Training with accurate MC for IBD signal and data for accidental background

- Cuts defined upon ANN outputs:
ANN performances

Before ANN cut

After ANN cut

ΔR (prompt-delay)

Δt (prompt-delay)
ANN performances

**Before ANN cut**

- Delayed energy spectrum
  - All vetoes applied

**After ANN cut**

- Prompt energy spectrum
  - ND

- Delayed energy spectrum
  - ND
ANN performances

- Accidental background dramatically reduced: ~ 4/day
- n-(Gd+H) analysis gives × 2.5 increase in statistics wrt n-Gd analysis:

\[ R_{IBD}: \sim 140/\text{day} \text{ @ FD; } \sim 800/\text{day} \text{ @ ND} \text{ (after all vetoes)} \]
\( \theta_{13} \) results

- Results presented at CERN in Sept 2016
- Data analyzed: FD-I & reactor-off data in SD mode, FD-II & ND data in MD mode
Rate + shape fit results

ND

FD-I

FD-II

\[ \sin^2(2\theta_{13}) = 0.119 \pm 0.016 \text{ (stat. + syst.)} \]
\[ \chi^2_{\text{min}}/n_{\text{dof}} = 236.2/114 \]

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>FD estimate</th>
<th>FD fit output</th>
<th>ND estimate</th>
<th>ND fit output</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^9\text{Li})</td>
<td>2.59 ± 0.61 d(^{-1})</td>
<td>2.55± 0.23 d(^{-1})</td>
<td>11.11 ± 2.96 d(^{-1})</td>
<td>14.4 ± 1.2 d(^{-1})</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>2.54 ± 0.07 d(^{-1})</td>
<td>2.51 ± 0.05 d(^{-1})</td>
<td>20.77 ± 0.43 d(^{-1})</td>
<td>20.85 ± 0.31 d(^{-1})</td>
</tr>
</tbody>
</table>
Data to data fit

\[
\sin^2(2\theta_{13}) = 0.123 \pm 0.023 \text{ (stat. + syst.)}
\]

\[
\chi^2_{\text{min}}/n_{\text{dof}} = 10.6/38
\]

\(\theta_{13}\) result not affected by spectral distortion
Comparison with other experiments

- Double Chooz
  JHEP 1410, 086 (2014)

- Preliminary
  (CERN seminar 2016)

- Daya Bay
  PRL 115, 111802 (2015)

- RENO
  PRL 116 211801(2016)

- T2K
  PRD 91, 072010 (2015)
  \( \Delta m^2_{32} > 0 \)
  \( \Delta m^2_{32} < 0 \)

- NOvA
  Preliminary (private communication)
  \( \Delta m^2_{32} > 0 \)
  \( \Delta m^2_{32} < 0 \)

- DC \( \theta_{13} \) (and accelerators) higher than other \( \theta_{13} \) values (2.2\( \sigma \) tension with DB)

- Redundancy between reactor experiments is **fundamental**: \( \theta_{13} \) is a key parameter for future \( \delta_{CP} \) measurements
DC $\theta_{13}$ prospects

- Not limited anymore by statistics with MD analysis
- **Proton number** (in the full NT+GC volume) is the largest systematic uncertainty (embedded in detection systematics)
  - NT+GC: 0.76 % relative near/far
  - NT: 0.1 % relative near/far
- DC largely dominated by proton # uncertainty
  - Most conservative assumptions were adopted here
  - Possibility to improve proton # knowledge (analysis & hardware)
Near detector shape comparison

DC: 210 000 events / DB: 1.2 million events / RENO: 280 000 events

DATA/MC ratio comparison

- $^{238}$U neutrino flux spectra different in DC (Haag) and DB/RENO (Huber)
- different reactor fuels

- Double Chooz (shape only)
- Daya Bay
- RENO (modified for shape only)
- NEOS (modified for shape only)

DC Preliminary

* can slightly differ from one experiment to another due to detector effects
Conclusions

- DC results with two detector and new IBD selection strategy (n-(Gd+H)):
  - Now largest $\theta_{13}$ single-detector target
  - Innovative analysis techniques (ANN) to efficiently reduce backgrounds and maximize detection efficiency
  - Reactor flux uncertainties almost fully cancelled thanks to DC isoflux configuration
  - Adopted conservative scenario in the evaluation & treatment of systematic uncertainties

- DC best value: $\sin^22\theta_{13} = 0.119 \pm 0.016$
  - Dominated by proton # uncertainty
  - Work in progress to achieve $\sin^22\theta_{13}$ precision < 0.01