First double-detector results from Double Chooz experiment

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on behalf of the Double Chooz collaboration
150 scientists in 7 countries

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project manager: Christian Veyssière (CEA Saclay)
Double Chooz is pioneer of reactor experiments to measure the $\theta_{13}$

- Improvements from Chooz w/ stable Gd-LS & new det. structure (Proposal@2006)
- First indication of non-zero $\theta_{13}$ at 94% C.L. (LowNu@2011, PRL 108 (2012) 131801)
- First $\theta_{13}$ results using Hydrogen capture signal (PLB 723 (2013) 66-70)
- $\theta_{13}$ measurements with multi-detector setup (Since 2015, this talk)

Features of reactor $\theta_{13}$ measurement

- Reactor is free and rich $\bar{\nu}_e$ source
- Direct measurements of $\theta_{13}$ with $\bar{\nu}_e$ disappearance at 1 km baseline as:
  \[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) + O(10^{-3}) \]
- Background is strongly suppressed by delayed coincidence technique
- Systematic uncertainties are further reduced by two identical detectors
Detection principle of reactor neutrinos

Two independent samples of Gd/H capture measured by delayed coincidence technique

- Prompt signal (e+ ionization & annihilation)
  \( E_{\text{prompt}} = 1 \sim 8 \text{ MeV} \)
- Delayed signal (Neutron capture)
  \( E_{\text{delayed}} = \sim 8 \ (2.2) \text{ MeV for Gd (H) capture} \)
- Time coincidence of those
  \( \tau \sim 30 \ (200) \mu s \text{ for Gd (H) capture} \)

In this IBD process, prompt energy is related to neutrino energy

\[
E_{\text{vis}} = E_{\text{kin}}e^+ + 2m_e \\
\approx E_{\bar{\nu}e} - (M_n - M_p) + m_e \\
\approx E_{\bar{\nu}e} - 0.782 \text{ MeV}
\]

→ Spectral shape of the prompt signal gives us further information.
Experimental site

L = ~400 m
~120 m.w.e.
10 m³ target

Operating since 2011

Reactors

EDF
Electricité de France

Two reactor cores
4.27 GW\(\text{th}\) for each core

Near detector

L = ~400 m
~120 m.w.e.
10 m³ target

Operating since 2015

Far detector

L = ~1050 m
~300 m.w.e.
10 m³ target

Operating since 2011

Started Double-detector data taking since early-2015
Double Chooz detector

**Inner Detector (ID)** - three cylindrical layers

- **ν-target (Gd capture) region**
  - Gd-loaded (1 g/l) liquid scintillator (10.3 m$^3$)

- **γ-catcher (H capture) region**
  - 22.3 m$^3$ liquid scintillator

**Buffer region**
- 110 m$^3$ mineral oil & 390 low-BG 10” PMTs

**Detectors for background veto**

- **Inner veto (IV)**
  - Liquid scintillator & 78 8” PMTs in steel tank

- **Outer veto (OV)**
  - Plastic scint. strip + WLS fiber + MAPMT
Single-detector & Double-detector phase

No ND

Single-detector (SD) phase

- Reactor B1
- Bugey4 (virtual)
- FD-I
- ~1km

Double-detector (DD) phase

- Reactor B1
- Bugey4 (virtual)
- ND
- FD-II
- ~0.4 km

SD: Bugey4 is used as an anchor of reactor ν flux (1.7% precision)
→ Nearly iso-flux setup of ND & FD can suppress ν flux error (< 0.1%)
→ Identical detector can cancel correlated systematics like det. efficiency.

Preliminary results using FD-I, FD-II and ND data (~461, 212, 150 days of live time) are shown in this talk.
Observed IBD rate: ~40 d$^{-1}$ (FD) and ~300 d$^{-1}$ (ND)

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

(□) : mimic prompt (delayed) signal
IBD candidates & BG estimation

Prompt signal energy w/ BG

All BG are measured from data:
- Accidental BG: Off-time coincidence (rate & shape)
- Fast-n + stop-μ: High energy window (rate), IV/OV tagged events (shape)
- Cosmogenic BG: $^9$Li-enriched data (shape)
  → $^9$Li BG rate is not used in the fit, which is constrained by shape in the fit

<table>
<thead>
<tr>
<th></th>
<th>FD-I</th>
<th>Reactor off</th>
<th>FD-II</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live time (d)</td>
<td>460.93</td>
<td>7.24</td>
<td>212.21</td>
<td>150.76</td>
</tr>
<tr>
<td>IBD prediction (d$^{-1}$)</td>
<td>38.04±0.67</td>
<td>0.217±0.0065</td>
<td>40.39±0.69</td>
<td>280.5±4.7</td>
</tr>
<tr>
<td>Accidental BG (d$^{-1}$)</td>
<td>0.070±0.003</td>
<td>0.106±0.002</td>
<td>0.344±0.002</td>
<td></td>
</tr>
<tr>
<td>Fast-n + stop-μ (d$^{-1}$)</td>
<td>0.586±0.061</td>
<td>3.42±0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosmogenic BG (d$^{-1}$)</td>
<td>(0.97±0.41)</td>
<td>(5.01±1.43)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total prediction (d$^{-1}$)</td>
<td>39.63±0.73</td>
<td>1.85±0.30</td>
<td>42.06±0.75</td>
<td>289.3±4.9</td>
</tr>
<tr>
<td>IBD candidates (d$^{-1}$)</td>
<td>37.64</td>
<td>0.97</td>
<td>40.29</td>
<td>293.4</td>
</tr>
<tr>
<td>(Number of events)</td>
<td>(17351)</td>
<td>(7)</td>
<td>(8551)</td>
<td>(44233)</td>
</tr>
</tbody>
</table>
Suppression of systematic uncertainties

SD phase: we improved uncertainties. Reactor ν flux error was dominant.
→ It is strongly suppressed with two detectors

DD phase: All systematic uncertainties are < 0.4% (after Rate + shape analysis)
→ Precision is now limited by Statistics. Further improvement is expected!
Preliminary results

Fit FD-I, FD-II and ND data simultaneously w/ predictions
- Chi-square method with systematic errors by pull term & covariance matrix
- Correlation of systematic uncertainties b/w detector periods are considered
- BG rate and shape are estimated from data (Li9 rate is not constrained)
- Observed data in reactor-off period is used → Further BG constraint

Best-fit: $\sin^2 2\theta_{13} = 0.111 \pm 0.018$ ($\chi^2$/dof = 128.8/120)
Non-zero $\theta_{13}$ observation at 5.8 $\sigma$ C.L.
Current $\theta_{13}$ in the world

Comparison of $\theta_{13}$ measurements

- Double Chooz
  [JHEP 1410 (2014) 086]
  Preliminary results shown in this talk

- Daya Bay
  [PRL 115 (2015) 111802]

- RENO
  [PRL 116 (2016) 211801]

- T2K
  [PRD 91 (2015) 972010]

T2K results w/ Reactor $\theta_{13}$
[PRD 91 (2015) 972010]

NOvA results w/ Reactor $\theta_{13}$
[PRL 116 (2016) 151806]

Precise measurement of $\theta_{13}$ by reactor experiments is still a key for current/future $\nu$ projects for CP violation and mass hierarchy → Validation with multiple experiments is essential.
To reach better precision, earlier:
Current analysis (Gd-only) is statistically limited
→ Inclusion of H-capture event (Gd+H analysis!)

Pros: Larger volume as target
Cons: Increase of Accidental BG by lowering $E_d$ window
Systematic error is also challenging
→ Analytical effort is on going… (Next page)
To reach better precision...

- Accidental BG is dramatically reduced by ANN
  → Almost negligible impact to $\theta_{13}$ measurement after ANN
- Confirmed $\times 2.5$ of IBD rate than Gd only analysis

New analysis is ongoing w/ more stat. & better understandings of syst.
→ We aims to release our results at CERN seminar (20th Sep.) Stay tuned!
Neutrino directionality

Direction of incoming $\nu$ can be observed by a vector from delayed to prompt signals

<table>
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<tr>
<th>Reactors’ direction from ND</th>
<th>$\phi(\degree)$</th>
<th>$\theta(\degree)$</th>
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<tbody>
<tr>
<td>B1</td>
<td>-70.23±0.38</td>
<td>84.90±0.23</td>
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<tr>
<td>B2</td>
<td>-53.55±0.49</td>
<td>83.23±0.27</td>
</tr>
<tr>
<td>B1+B2</td>
<td>-62.09±0.64</td>
<td>84.08±0.35</td>
</tr>
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Direction to:
- Reactor B1
- Reactor B2

Sterile neutrino search

Sterile $\nu$ hypothesis can be tested by DC detectors located in ~400 m baseline (ND) and ~1 km baseline (FD)

Expected sensitivity for 3 years operation

$\Delta m^2_{4i}/eV^2$

Double Chooz PRELIMINARY
95% CL sensitivity
Conclusion

- Reactor $\theta_{13}$ is a key for current and future neutrino projects
  $\rightarrow$ Validation by multi-experiment is essential

- First $\theta_{13}$ results is reported with the double-detector setup in Double Chooz experiment
  $(FD-I: 460.93 \text{ d} + FD-II: 212.21 \text{ d} + ND: 150.76 \text{ d})$
  $\rightarrow \sin^22\theta_{13} = \sin^22\theta_{13} = 0.111 \pm 0.018$
  - Reactor flux is strongly suppressed to <0.1% by ND
  - Other systematic uncertainties are suppressed well below 1%

- The precision is currently limited by Statistics
  $\rightarrow$ New $\theta_{13}$ results with Gd+H analysis will come soon
  - Other physics programs are also expected

Poster presentations from Double Chooz experiments:
D. Kaplan et al., Reactor spectral rate and shape measurement in Double Chooz detectors
A. Meregaglia et al., IBD background rejection and tagging at the Double Chooz experiment
G. Yang, et al., $\theta_{13}$ oscillation analysis in Double Chooz with two detectors
T. Matsubara et al., Sterile neutrino search in the Double Chooz experiment
Detector performance

Detector performance is evaluated by
- Various sources like $^{60}\text{Co}$, $^{68}\text{Ge}$, $^{137}\text{Cs}$, $^{252}\text{Cf}$ with two deployment systems: **Z-axis system** & **Guide tube system**
- Natural sources like neutron capture on H/Gd or BiPo

Cf-252 source deployed at detector center

We precisely evaluated detection efficiency, energy scale, uniformity and stability from the systems and/or sources.
Rate of IBD candidates with background subtracted

ND
1 reactor on 2 reactors on

FD-II

Same variation of IBD candidates in double detector phase