The Double Chooz reactor neutrino experiment

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On behalf of
the Double Chooz collaboration
Neutrino Oscillation

\[ s_{ij} = \sin \theta_{ij}, \quad c_{ij} = \cos \theta_{ij} \]

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric: \( \nu_\mu \rightarrow \nu_\mu \)

Super-K+K2K+MINOS

\[ \sin^2 \theta_{23} = 0.50^{+0.08}_{-0.07} \]

\[ \Delta m_{23}^2 = (2.5^{+0.20}_{-0.25}) \times 10^{-3} \text{ eV}^2 \]

Reactor etc.: CHOOZ

\[ \sin^2(2\theta_{13}) < 0.15 \]

Solar: \( \nu_e \rightarrow \nu_x \)

Solar+KamLAND

\[ \sin^2 \theta_{12} = 0.30^{+0.02}_{-0.03} \]

\[ \Delta m_{12}^2 = (7.9 \pm 0.3) \times 10^{-5} \text{ eV}^2 \]

Recent T2K, MINOS results

• Remaining parameters \( \Rightarrow \theta_{13} \), CP-violating phase \( \delta \), Mass hierarchy
Reactor Neutrino Experiment w/ multi detectors

- Reactor ➔ Intense nu source
- Pure $\theta_{13}$ measurement
  ✓ Independent from CP-violating phase $\delta$
  ✓ Small matter effect
- Multi detector concept
  ✓ Significant reduction of systematic errors

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

$\Delta m^2 = 7.65 \times 10^{-5}$ eV$^2$
$\Delta m^2 = 2.40 \times 10^{-5}$ eV$^2$
Double Chooz Experiment

Chooz Reactors
4.27GW_{th} x 2 cores

Far Detector
<L> 1050m
70\nu/day
300m.w.e.

Near Detector
<L> 400m
400\nu/day
120m.w.e.

Reactor Neutrino Oscillation

\[ P(\nu_e \rightarrow \bar{\nu}_e) \]
Double Chooz Collaboration

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Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.in2p3.fr
Double Chooz Detector

New 4-region large detector concept

- **Outer Veto:** plastic scintillator strips (400 mm-t)
- **ν-Target:** 10.3 m$^3$ scintillator doped with 0.1g/l of Gd in an acrylic vessel (8 mm-t)
- **γ-Catcher:** 22.3 m$^3$ scintillator in an acrylic vessel (12 mm-t)
- **Buffer:** 110 m$^3$ of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs
- **Inner Veto:** 90m$^3$ of scintillator in a steel vessel equipped with 78 PMTs
- **Veto Vessel (10mm) & Steel Shielding**
Neutrino Detection

Prompt signal
position
(1~8 MeV)

\[ \nu_e \rightarrow p \rightarrow e^+ \rightarrow e^- \]

\[ \tau = 30 \mu s \]

Delayed signal
capture
(~8 MeV)

\[ n + Gd \rightarrow \text{neutron capture} \]

Cross Section
\(~10^{-43} \text{cm}^2\)

Reactor Spectrum

Observed Spectrum
Milestones

• May 2008 - October 2010
  Far detector construction.
• December 2010
  Far detector filling completed.
• April 2011
  Far detector commissioned.
• April 2011
  ✓ Start physics data taking with far detector.
  ✓ Near laboratory construction started.
• July 2011
  Outer veto commissioned.
• November 2011
  FIRST DATA
• June 2012
  Near laboratory expected delivery.
• Beginning 2013
  ➢ Near detector expected.
  ➢ Data taking with two detectors.
Recent work defining new reference on the neutrino flux prediction
- New flux calculation $\Rightarrow +6\%$

- All reactor neutrino experiment are below
  - use Bugey4 anchoring (as CHOOZ) $\Rightarrow$ Far phase
  - use 2 detectors $\Rightarrow$ Near & Far phase
Neutrino Flux Uncertainties

- Total flux uncertainty budget dominated by Bugey4 anchoring point (like in CHOOZ)

- Very detailed simulation of all reactor cycle (MURE) and fuel evolution [reactor data input]

Total error =1.7%
Number of data taking days: **206 days**

Integrated data taking time in total: **177.4 days**

Integrated data taking time for physics: **159.6 days**

Data taking efficiency in total: **86.2 %**

Data taking efficiency for physics: **77.5 %**
Detector Stability

- neutron capture on proton after muon

(Double Chooz preliminary)
Neutrino Selection

- Discard all triggers in 1ms after each muon
- PMT spontaneous light emission rejection cuts (using ratio $Q_{\text{max}}/Q_{\text{total}}$, RMS of hit-time per PMT)

- Prompt signal within $[0.7, 12]$ MeV
- Delayed signal within $[6, 12]$ MeV
- Coincidence window between $[2, 100]$ μs
- Multiplicity condition
  - $E > 500$ keV
  - $-100\mu s < d\text{Time} < 400\mu s$
Neutrino Prompt Signal &
Trigger Efficiency

- Trigger threshold (defined as 50% efficiency) is 0.350 MeV
- Trigger efficiency is 100% +0/-0.4% above 0.7 MeV

⇒ No Prompt Energy Cut Inefficiency
Selection of Neutron Capture on Gd only
- Allow to define the fiducial volume by the mass of Gd-loaded LS
- Delayed Energy Cut Efficiency : 0.86 +/- 0.6%.

The efficiency within [2,100] μs is 0.965 ± 0.5%
Vertex Reconstruction

Double Chooz preliminary

Double Chooz preliminary

Double Chooz preliminary

Double Chooz preliminary
Prompt energy vs Delayed energy

\[ E_{\text{prompt}} \text{ vs } E_{\text{delayed}} \]
Background

- Accidental Background
  - prompt-like signal: radioactivity from materials, PMTs, surrounding rock
  - n signal: n from cosmic μ spallation,

- Correlated BG
  - Fast neutrons (by cosmic μ) gives recoil protons and are captured on Gd.
  - Stopping-muons followed by muon-decay (Michel electron)
  - Long-lived (9Li, 8He) β+n-decaying isotopes induced by μ.
Accidental Background

- on time window: [2,100]μsec
- off time window: [1002,1100]μsec

Rate=(0.332±0.004)day⁻¹
Double Chooz preliminary

9Li/8He Background

- 9Li events selection:
  - Statistical
  - Search for a triple delayed coincidence between showering muon and neutrino-like coincidence

- Showering muon: E>600 MeV

- Δt between showering muon and prompt event is given by the $^9\text{Li}$ life time (257ms).

**Rate:** 2.3 \(-1.2 +1.2\) per Day

Ref. 257ms
Fast Neutron Background

- Neutrino Analysis with prompt energy extended to 30 MeV

- Two populations:
  - Fast-n
  - Stopping-muon

- Rate:
  - Extrapolation from high Energies to lower ones
  - 0.7 -0.5 +0.5 per Day

- Spectrum:
  - Flat
  - + Stopped Mu Shape Unc.

Rate=0.7 -0.5 +0.5 per Day
Reactor off-off data

- Second reactor OFF for one day

- 3 events <30MeV
  - two possible Li/He candidates
  - one consistent with stopping-muon candidate
θ_{13} Preliminary Results

- **Rate + Shape Analysis:**
  \[
  \sin^2(2\theta_{13}) = 0.085 \pm 0.029\text{(stat)} \pm 0.042\text{(syst)}
  \]

- **Rate Only:**
  \[
  \sin^2(2\theta_{13}) = 0.093 \pm 0.029\text{(stat)} \pm 0.073\text{(syst)}
  \]
Combined best fit point is at 0.092
θ₁₃ = 0 is excluded at 3 sigma from T2K+DC
Conclusions

- Far Detector
  - Data taking since April 2011
  - Report of Analysis of 100 days of data.
  - Hint for positive value of $\theta_{13}$
    - $\sin^2(2\theta_{13}) = 0.085 \pm 0.029^{\text{stat}} \pm 0.042^{\text{syst}}$
    - No-Oscillation excluded at 92.1% CL

- Near Detector
  - Detector completed until end of 2012
  - Far + Near detector data taking:
    - Beginning of 2013