The Double Chooz experiment

Christian Buck, MPIK Heidelberg on behalf of the Double Chooz Collaboration

NOW 2016, Otranto
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Reactor antineutrinos

3 MeV reactor antineutrino flux worldwide

Antineutrino Global Map 2015, Sci.Rep.5 (2015) 13945

Reactors: Strong and pure source of MeV e-antineutrinos

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Neutrino mixing at reactors

Short baseline experiments "Reactor anomaly"

$\theta_{13}$ exp.: Double Chooz Daya Bay RENO

KamLAND: "Solar" Parameters

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) L(m)}{E_\nu (MeV)}\right)$
Double Chooz site

Near detector (ND):
Data taking 01/2015

Far detector (FD):
Data taking 04/2011

2 x 4.25 GW\textsubscript{th} ≈ 10^{21} \text{ neutrinos/s}

Neutrino oscillations

Christian Buck, MPIK Heidelberg
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.
- Kitasato 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
Neutrino production / detection

\[ N_{\nu}^{\text{exp}}(t) = \frac{\varepsilon N_p}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle \]

Mean cross section per fission (Bugey anchor point for FD only)

\[ E_{\text{vis}} = E_{\nu} - 0.8 \text{MeV} \]

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

Prompt: > 1MeV

Delayed: n on Gd (H)
30 (200) µs
8 (2.2) MeV

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Detector Design

Inner detector:

Target (r = 1.2 m):
- Acrylic vessel (8 mm)
- 8.3 tons Gd-scintillator (1 g/l Gd, o-PXE based)

Gamma Catcher (0.55 m):
- Acrylic vessel (12 mm)
- 18 tons liquid scintillator (o-PXE based)

Buffer (1.05 m):
- Steel (3 mm)
- 80 tons “oil”
- 390 PMTs (10”)

Outer Veto:
- Plastic scintillator

Inner Veto:
- Steel (8 mm)
- 70 tons LS (LAB based)
- 78 PMTs (8”)
Calibration systems:
- LED light injection (multi wavelengths)
- Vertical z-axis (radioactive sources, laser ball)
- GC guide tube (radioactive sources)
- Natural sources (spallation neutrons)
Energy scale

- Response uniformity
- Non-linearity effects
- Time variation
Detector stability

- Time variation detector response: < 1%/year
- Gd fraction (center) stable since > 5 years on 0.2% level
Double Chooz milestones

| Year  | Event Description                                      | Reference   |
|-------|--------------------------------------------------------|-------------|
| 2011  | Start data taking (far only) and first results         |             |
| 2012  | First analysis with n captures on H                    |             |
| 2013  | RRM (rate) analysis and near lab delivery              |             |
| 2014  | Spectral distortion (reactor flux correlation)         |             |

**Accelerator Experiments**
- Normal Hierarchy
- Inverted Hierarchy

**Reactor Experiments**
- Rate only
- Rate+Spectral
- n-Gd
- n-H

**Global Fit**
- PDG 2013

**Best Fit + 68% C.L.**

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\[
\sin^2 2\theta_{13}
\]
2016: First DC two detector result

**Double Chooz**
JHEP 1410, 086 (2014)

**Preliminary (Moriond)**

**Daya Bay**
PRL 115, 111802 (2015)

**RENO**
Preprint (arXiv:1511.05849)

**T2K**
PRD 91, 072010 (2015)

\[ \Delta m^2_{32} > 0 \]

\[ \Delta m^2_{32} < 0 \]

\[ \sin^2(2\theta_{13}) = 0.111 \pm 0.018 \]

Preliminary result shown at Moriond conference (9 months data)

Limited by statistics
**Signal and backgrounds**

**FD-I (460.93days)**

**FD-II (212.21days)**

**ND (150.76days)**

| Events/day FD | Events/day ND |
|---------------|---------------|
| IBD candidates | 40.29         | 293.4         |
| Cosmogenic BG  | 0.75±0.14     | 4.89±0.78     |
| Fast n+stop-μ BG | 0.535±0.035  | 3.53±0.16     |
| Accidental BG  | 0.106±0.002   | 0.344±0.002   |

*S/B > 25!*
Fit results (Moriond)

Data-MC comparison for each configuration

Best-fit: \( \sin^2 2\theta_{13} = 0.111 \pm 0.018 \) (stat.+syst.) \( (\chi^2/\text{dof} = 128.8/120) \)
Dominant uncertainty:
Background DC-I ➔ Reactor flux (SD) ➔ Statistics (Moriond) ➔ Detection systematics?
DC statistics

Moriond analysis limited by statistical power

IBD(Gd) IBD(Gd+H)

10 m³ → 30 m³

Systematics!

Improve statistics by almost factor 3!
(about 200 000 ν in ND and 80 000 ν in FD)
IBD candidates vs time

IBD (Gd + H): 140 per day (S/B > 10)

IBD (Gd + H): 900 per day (S/B > 20)
Accidental Background

Rate (d⁻¹) comparison

|        | Before ANN | After ANN |
|--------|------------|-----------|
| Gd     | 0.07       | 3.1       |
| H-2013 | 73         | 4.3       |
| H-2016 | 4          | 4         |
| Gd+H (FD) | 4    | 3.1       |
| Gd+H (ND) | 4    | 3.1       |

**With ANN**

- Accidental reduction using Artificial Neural Network (ANN)
- Rate estimation using off-time window method
Cosmogenic isotopes

- Long-lived $\beta$-n emitters ($^9$Li and $^8$He) produced by spallation interactions of muons
- Li sample using distance to muon track and n multiplicity
- Contribution of $^8$He compatible with 0
- Dominant background in previous Gd analyses (FD only)
- Rates: ND $\approx$ 11/day, FD $\approx$ 2.6/day
Fast neutrons and stopping muons

- More critical in near detector (Some LS in Buffer)
- Fast neutrons reduced using Inner Veto coincidences
- Measure up to 100 MeV
- Rates: ND ≈ 20/day, FD ≈ 2.5/day
Background reduction

Delayed energy spectrum before and after event rejection with different cuts and vetos

Entry / 0.1 MeV

Visible Energy (MeV)
Both reactors off data

- Unique for Double Chooz!
- Two periods: 7.24 days total (FD only phase)
- Constrains background in $\theta_{13}$ fit

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Excess events in 4 – 6 MeV region (Gd and H)
Also seen in Daya Bay and RENO
Dependence on fission isotopes?
Physics beyond $\theta_{13}$

- Muon capture  
  (DC, PRC 93, 054608, 2016)
- Ortho-positronium  
  (DC, JHEP 10 (2014) 032)
- Background studies  
  (DC, PRD 87 (2013) 011102(R))
- Lorentz violation  
  (DC, PRD 86, 112009, 2012)
- Sensitivity to $\Delta m_{13}^2$
- Neutrino directionality
- Sterile neutrino studies
Double Chooz taking data with 2 detectors since start of 2015

- Preliminary result: $\sin^2(2\theta_{13}) = 0.111 \pm 0.018$
- Improved statistics with Gd+H analysis (factor 5)
- Good background control ($S/B > 10$)
- New result with improved sensitivity soon!
- Further shape studies with high statistics in ND
Backup
Sensitivity projection

![Graph showing sensitivity projection over time]

- **DC-IV Moriond Projection**
- Uncertainty on $\sin^2\theta_{13}$:
  - $0.030$ (expected by Moriond)
  - $0.018$ (<1 year)
  - $0.010$ (~5x years)
- Dominated by statistics for ~10 years

- **Dates:**
  - 05-Sept-16
  - Christian Buck, MPIK Heidelberg
Response non-linearity

\[
\frac{\sigma}{E_{\text{vis}}} = \sqrt{\frac{a^2}{E_{\text{vis}}} + b^2 + \frac{c^2}{E_{\text{vis}}}}
\]

- \(a\): statistical
- \(b\): constant term
- \(c\): electric noise

|       | FD-I  | FD-II | ND    |
|-------|-------|-------|-------|
| \(a\) | 7.84 ± 0.10 % | 7.92 ± 0.17 % | 8.46 ± 0.09 % |
| \(b\) | 1.87 ± 0.06 % | 1.66 ± 0.11 % | 1.58 ± 0.10 % |
| \(c\) | 2.49 ± 0.29 % | 2.13 ± 0.35 % | 2.32 ± 0.21 % |
IBD selection

Energy

Distance

Time

Good data: MC agreement!
## Signal and backgrounds

|                     | IBD(Gd)          | IBD(Gd+H)        |
|---------------------|------------------|------------------|
|                     | FD-I  | FD-II | ND     | FD-I  | FD-II | ND     |
| Accidentals (/day)  | 0.069 ± 0.002   | 0.118 ± 0.006   | 0.303 ± 0.007 | 3.994 ± 0.004 | 4.284 ± 0.009 | 3.104 ± 0.004 |
| Fast Neutrons (/day)| 0.47 ± 0.03     | 4.00 ± 0.15     |         | 2.54 ±0.07  | 20.77 ± 0.43  |         |
| Cosmogenics (/day)  | 0.87 ± 0.42     | 4.67 ± 1.42     |         | 2.59 ± 0.61  | 11.11 ± 2.96  |         |
| Reactor OFF (/day)  | 0.76 ± 0.38     |       |         | 8.90 ± 1.20  |       |         |
| exp. ΣBG (/day)     | 1.43±0.42       | 8.97±1.43       |         | 9.13±0.61    | 9.42±0.61     | 34.98±2.99  |
| IBD cand. - ΣBG (/day) | 35.82 | 40.54 | 303.52 | 96.64 | 108.11 | 780.96 |
| Signal/ΣBG         | 25.00 | 28.40 | 33.80  | 10.60 | 11.50 | 22.30  |
| Signal/σ(BG)       | 85.29 | 96.52 | 212.25 | 158.43 | 177.23 | 261.19 |
Background Vetoes (Gd)

- **FV veto** ⇒ chimney stop-μ
- **μ veto** ⇒ 1ms veto after μ
- **Multiplicity** ⇒ unicity condition
- **FV veto** ⇒ vertex likelihood
- **IV veto** ⇒ IV activity
- **OV veto** ⇒ OV activity
- **Li veto** ⇒ Li-likelihood
- **LN cut** ⇒ PMT hit pattern & time
- **LI veto** ⇒ cosmogenic 9Li
- **(CPS veto)** ⇒ chimney likelihood
- **(Qratio)** ⇒ Max Q/Tot. Q
- **Li veto** ⇒ cosmogenic 9Li
- **μ veto** ⇒ μ, cosmogenic
- **Multiplicity** ⇒ multiple-n
- **FV veto** ⇒ chimney stop-μ
- **IV veto** ⇒ fast n, stop-μ, γ scattering
- **OV veto** ⇒ fast n, stop-μ
- **Li veto** ⇒ cosmogenic
- **LN cut** ⇒ light emission from PMT
- **LI veto** ⇒ stop-μ
- **(CPS veto)** ⇒ stop-μ
- **(Qratio)** ⇒ ND buffer stop-μ

(only applied in multi-detector analysis)
## Reactor flux uncertainty

|                  | FD-I (%) | FD-II (%) | ND (%) |
|------------------|----------|-----------|--------|
| Bugey4           | 1.40     | 1.40      | 1.40   |
| Energy per fission | 0.16    | 0.16      | 0.16   |
| Spectrum⊕σ_{IBD} | 0.20     | 0.20      | 0.20   |
| Baselines        | < 0.01   | < 0.01    | 0.01   |
| Fission fraction (α_k) | 0.82   | 0.74      | 0.73   |
| Thermal power (P_{th}) | 0.44   | 0.44      | 0.44   |
| **Total**        | **1.70** | **1.66**  | **1.66** |

- **Correlated** across FD-I, FD-II and ND
- **Uncorrelated** ⇒ suppressed with two detectors (in parallel operation)

\[ \rho(\text{FD-I:FD-II}) = 0.72 \ (0.90\% \ relative) \]
\[ \rho(\text{FD-II:ND}) = >0.99 \ (0.07\% \ relative) \]

Inter-reactor correlation for α_k and P_{th}: ρ_{B1/B2} = 0.78 (most conservative assumption with current data set)