The Double Chooz experiment

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

Neutrino Telescopes, Venice
March, 3rd 2015
Neutrino mixing at reactors

Reactors: Strong and pure source of MeV e-antineutrinos

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\Theta_{13} \sin^2 \left( 1.27 \frac{\Delta m_{13}^2 (eV^2) L(m)}{E_\nu (MeV)} \right) \]

No parameter degeneracy!
Double Chooz site

Running since 04/2011

Data taking 12/2014

2 x 4.25 GW$_{th}$

$\approx 10^{21}$ neutrinos/s
Double Chooz: „Only“ two reactors, but almost iso-flux
⇒ Low statistics, but good for systematics!

« Reactor Neutrino Flux Uncertainty Suppression on Multiple Detector Experiments »
arXiv:1501.0356
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.
Niigata 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

03-Mar-15
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Neutrino production / detection

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

Mean cross section per fission (Bugey anchor point!)

\( \bar{\nu}_e + p \rightarrow e^+ + n \)

Prompt: > 1MeV

Delayed:
- \( n \) on Gd (H)
- 30 (200) \( \mu s \)
- 8 (2.2) MeV

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

Inner detector:

Target \( (r = 1.2 \text{ m}) \):
- 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)
- 18.1 tons liquid scint.
  (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”)

Steel shielding
(15 cm)
Calibration systems:
- LED light injection (multi wavelengths)
- Vertical z-axis (radioactive sources, laser ball)
- GC guide tube (radioactive sources)
- Natural sources (spallation neutrons)
Double Chooz milestones

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 and near det. data taking

"Gd-III" publication: Double Chooz Collaboration, JHEP10(2014)086
Energy scale

Visible energy reconstruction
- Detector uniformity
- Time stability
- Non-linearities

Total uncertainty of 0.74 %
Neutrino selection (Gd)

**Modified selection for optimized S/B ratio (> 20)**

<table>
<thead>
<tr>
<th>Muon veto</th>
<th>&gt; 1 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>„Light noise“</td>
<td>Uniform (space) and simult. (time)</td>
</tr>
<tr>
<td>Correlated Background reduction</td>
<td>Use Inner/Outer veto and vertex reconstruction information</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>&lt; 1 m</td>
</tr>
<tr>
<td>Prompt energy</td>
<td>0.5 – 20 MeV</td>
</tr>
<tr>
<td>Delayed energy</td>
<td>4 – 10 MeV</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>0.5 – 150 $\mu$s</td>
</tr>
<tr>
<td>Isolation window</td>
<td>(-200, + 600) $\mu$s</td>
</tr>
</tbody>
</table>

Modification to previous Gd publication (2012)

- Optimized
- New
- Wider range
Selection improvements

Improvements compared to 2012 analysis („Gd-II“ publication) clearly visible in energy spectra and correlation time distribution
Neutrino candidates

- Data from Apr 2011 – Jan 2013 (live-time: 460.7 days)
- 17351 neutrino candidates (doubled statistics)
- 18290 predicted events (no oscillation)
Detection efficiency

Evaluation of detection uncertainty using Cf data and IBD cand.

Total uncertainty: 0.6 % (dominated by Gd fraction)
Accidental background

Random coincidences determined by off-time window method
Constant rate of $0.070 \pm 0.003$ events / day
Fast neutrons and stopping muons

- Stopping muons effectively identified by PMT hit pattern
- Fast neutrons reduced using Inner Veto coincidences
- Rate extrapolated from high energies (flat spectrum): 0.60 ± 0.05 events / day
- Long-lived $\beta$-$n$ emitters ($^9$Li and $^8$He) produced by spallation interactions of muons in the detector
- Fit time correlation of IBD candidate and previous muon
- 55% rejection by $Li+He$ veto (distance to $\mu$ track, $#n$ after $\mu$)
- Rate after subtraction of rejected Li candidates

$$0.97^{+0.41}_{-0.16} \text{ events / day}$$
Both reactors off data

- Unique for Double Chooz!
- Two periods: 7.24 days total
- Residual neutrinos (simul.):
  - $1.57 \pm 0.47$ events
- Observed events:
  - 57 candidates selected
  - 7 remain after vetoes
- Constrains background in $\Theta_{13}$ fit
### Normalization uncertainties

Uncertainties relative to signal prediction

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>1.7%</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>0.6%</td>
</tr>
<tr>
<td>Background (Li + He)</td>
<td>+1.1 / -0.4%</td>
</tr>
<tr>
<td>Other systematics</td>
<td>≤0.1%</td>
</tr>
<tr>
<td>Statistics</td>
<td>0.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+2.3 / - 2.0%</td>
</tr>
</tbody>
</table>

Background errors further reduced by rate + shape fit
$\Theta_{13}$: rate + shape result

Gd analysis (467.9 live days) in Far Detector:

\[ \sin^2 2\Theta_{13} = 0.090^{+0.032}_{-0.029} \]
- Excess events in 4 – 6 MeV region (Gd and H)
- Background? Excess reactor flux correlated   not favored
- Energy scale? Confirmed by n on C and \(^{12}\)B   not favored
- Flux prediction? Under investigation
- No significant impact on \(\Theta_{13}\) measurement
Reactor rate modulation

- Compare obs. vs exp. rate for different reactor power cond.
- Rate only → spectrum and background model independent
- Extract $\Theta_{13}$ and background rate from linear correlation
## RRM results

<table>
<thead>
<tr>
<th></th>
<th>Free BG</th>
<th>off-off</th>
<th>BG constr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^{2}2\theta_{13}$</td>
<td>0.089 ± 0.052</td>
<td>0.060 ± 0.039</td>
<td>0.090 $^{+0.034}_{-0.035}$</td>
</tr>
<tr>
<td>BG rate (ev/day)</td>
<td>1.56 ± 0.86</td>
<td>0.093 $^{+0.43}_{-0.36}$</td>
<td>1.56 $^{+0.18}_{-0.16}$</td>
</tr>
</tbody>
</table>

Comparison with rate + shape analysis:

\[
\sin^{2} 2\theta_{13} = 0.090^{+0.032}_{-0.029}
\]

\[
BG(\text{ev / day}) = 1.64^{+0.41}_{-0.17}
\]
Physics beyond $\theta_{13}$

- Ortho-positronium
  (DC, JHEP 10 (2014) 032)

- Sensitivity to $\Delta m_{13}^2$

- Neutrino directionality
  (arXiv:1208.3628)

- Sterile neutrino
  (PRD 83 (2011) 073006)

- Background studies
  (DC, PRD 87 (2013) 011102(R))

- Lorentz violation
  (DC, PRD 86, 112009, 2012)
Near detector

- Started ND constr. 05/2013
- Data taking since 12/2014
- $r = 465 \text{ m} / 351 \text{ m}$
- Shielding 115 mw.e.
Spallation n captures Far (calib.) vs Near Detector (uncalib.) ➔ feasibility of IBD measurement

Preliminary study of ND singles indicates similar rate as in FD ➔ radiopurity and shielding goals achieved
Double Chooz sensitivity
Recent analysis improvements with Far Detector
- Improve accuracy of energy reconstruction
- Optimized selection, reduce detection systematics
- New background tagging and rejection techniques
- Include reactor off-off data in fit

Result rate + shape analysis:
$$\sin^2 2\Theta_{13} = 0.090^{+0.032}_{-0.029}$$

Independent cross-check analysis:
- Neutron captures on Hydrogen
- Reactor rate modulation analysis

Near detector data taking started
Backup
Reactor spectrum

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

\[ \langle \sigma_f \rangle = \langle \sigma_f \rangle^{\text{Bugey}} + \sum_k \left( \alpha_k^{\text{DC}}(t) - \alpha_k^{\text{Bugey}} \right) \langle \sigma_f \rangle_k \]

*Data from T. A. Mueller et al., arXiv:1101.2663v3*

**Bugey4 measurement as anchor point**

**Fission fraction in Chooz core**
Reactor simulation

- Regular monitoring of thermal power (T in primary loop every minute, weekly measurement of steam generator enthalpy balance)
- Fractional fission rates from U and Pu isotopes (burnup curves)
  - EDF inputs (fuel loading, geometry, power history, …)
  - Reactor simulations: MURE, Dragon
Reactor burnup

![Graph showing burnup curves for different isotopes](image)

Double Chooz preliminary

- $^{235}\text{U}$
- $^{239}\text{Pu}$
- $^{238}\text{U}$
- $^{241}\text{Pu}$

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Uncertainty on reactor predictions

Total: 1.7%
(2.7% without Bugey anchor point)
Reactor anomaly

From T. Lasserre, TAUP 2013

\[ R = 0.936 \pm 0.024 \] (2.7\(\sigma\) deviation from unity)
More on energy scale

**Graphs and Tables**

- Graph showing measured gain and best-fit gain function vs. charge.
- Graph showing variation over elapsed days.
- Table summarizing uncertainty and ratio of energy sources:
  - Non-uniformity: 0.36%, Gd-III/Gd-II: 0.84
  - Instability: 0.50%, Gd-III/Gd-II: 0.82
  - Non-linearity: 0.35%, Gd-III/Gd-II: 0.41
  - Total: 0.74%, Gd-III/Gd-II: 0.65

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Double Chooz Trigger Efficiency of Singles

- Trigger efficiency
- 1σ uncertainty (stat+sys)
- 50% efficiency at ~0.3 MeV
## MC correction

<table>
<thead>
<tr>
<th>Correction source</th>
<th>MC Correction</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAQ &amp; Trigger</td>
<td>1.000</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Veto for 1 ms after muon</td>
<td>0.955</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>IBD selection</td>
<td>0.989</td>
<td>0.2</td>
</tr>
<tr>
<td>FV, OV, IV, Li+He veto</td>
<td>0.993</td>
<td>0.1</td>
</tr>
<tr>
<td>Scintillator proton number</td>
<td>1.000</td>
<td>0.3</td>
</tr>
<tr>
<td>Gd fraction</td>
<td>0.975</td>
<td>0.4</td>
</tr>
<tr>
<td>Spill in/out</td>
<td>1.000</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.915</strong></td>
<td><strong>0.6</strong></td>
</tr>
</tbody>
</table>
Light noise

Preliminary

Data (ν candidates) Prompt signal

Preliminary

Data (ν candidates) delayed signal

Preliminary

MC Prompt signal

Preliminary

MC delayed signal
FV veto (delayed signal)

IBD signal  Stopping muons

„Light noise“
Details accidentals

Rate stability

Distance vertex positions

IBD signal inefficiency by $\Delta R$ cut: 0.3%
\( ^9\text{Li} \) background

\( ^9\text{Li} \) decays with a half-life of 178 ms. The decay modes include:

- \( \beta^- < 2.3 \text{ MeV} \) with 49.5% probability
- \( \beta^- < 10.8 \text{ MeV} \) with 2.5% probability
- \( \beta^- < 11.1 \text{ MeV} \) with 17% probability
- \( \beta^- < 13.6 \text{ MeV} \) with 28% probability
- \( \gamma = 11.3 \text{ MeV} \)

\( ^8\text{Be} + n \) decays to \( ^4\text{He} \) with an energy of 0.09 MeV.

\( ^8\text{He} \) and \( ^9\text{Li} \) can be produced in cosmic muon interactions.
Vetoes
## Fit parameters

<table>
<thead>
<tr>
<th>Fit Parameter</th>
<th>Input Value</th>
<th>Best-Fit Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li+He bkg. (d⁻¹)</td>
<td>0.97⁺⁻0.410.16</td>
<td>0.74 ± 0.13</td>
</tr>
<tr>
<td>Fast-n + stop-μ bkg. (d⁻¹)</td>
<td>0.604 ± 0.051</td>
<td>0.568⁺⁻0.0380.037</td>
</tr>
<tr>
<td>Accidental bkg. (d⁻¹)</td>
<td>0.0701 ± 0.0026</td>
<td>0.0703 ± 0.0026</td>
</tr>
<tr>
<td>Residual $\bar{\nu}_e$</td>
<td>1.57 ± 0.47</td>
<td>1.48 ± 0.47</td>
</tr>
<tr>
<td>$\Delta m^2$ (10⁻³ eV²)</td>
<td>2.44⁺⁻0.090.10</td>
<td>2.44⁺⁻0.090.10</td>
</tr>
<tr>
<td>E-scale $\epsilon_a$</td>
<td>0 ± 0.006</td>
<td>0.001⁺⁻0.0060.005</td>
</tr>
<tr>
<td>E-scale $\epsilon_b$</td>
<td>0 ± 0.008</td>
<td>-0.001⁺⁻0.0040.006</td>
</tr>
<tr>
<td>E-scale $\epsilon_c$</td>
<td>0 ± 0.0006</td>
<td>-0.0005⁺⁻0.00070.0005</td>
</tr>
</tbody>
</table>
Spectra including background (DC-II)
Combined fit

nGd data
April 2011-March 2012

nH data
April 2011-March 2012

Double Chooz Preliminary