Latest results of the Double Chooz reactor neutrino experiment

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On Behalf of the Double Chooz Collaboration

NUFACT - 25th September 2017
INTRODUCTION

- Reactor oscillation experiments aim at the measurement of $\theta_{13}$ through the observation of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ transition according to the oscillation probability:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m^2_{32} L}{4E} \right)$$

- The use of two detectors allows to measure the flux before and after the oscillation to cancel out the associated systematics.

- The advantages of this measurement with respect to long baseline oscillation experiments is a clean measurement of $\theta_{13}$ since:

  1. It is a disappearance experiment, therefore insensitive to the value of the $\delta$-CP phase.
  2. It has a short baseline (order of 1 km) and it is therefore insensitive to matter effects.
  3. The dependence on $\Delta m^2_{21}$ is very weak: $\mathcal{O} (\Delta m^2_{21}/\Delta m^2_{31})$. 

C. Jollet (IN2P3)
Double Chooz OVERVIEW

Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology
Data taking since December 2014

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e. hill topology
Data taking since April 2011

2 reactors
$P_{th} = 4.25$ GW each
Neutrinos are observed via Inverse Beta Decay (IBD):

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

The signal signature is given by a **twofold coincidence**:

1. Prompt photons from \( e^+ \) ionisation and annihilation (1-8 MeV).
2. Delayed photons from \( n \) capture on Gadolinium (~8 MeV) or H (2.2 MeV).
3. Time correlation: \( \Delta t \sim 30 \mu s \) for Gd and \( \Delta t \sim 200 \mu s \) for H.
4. Space correlation (< 1m).

The energy spectrum is a convolution of flux and cross section (threshold at 1.8 MeV).

The prompt energy is related to \( \bar{\nu}_e \) energy:

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

The survival probability depends on \( E_\nu \) therefore we have a measurement of \( \theta_{13} \) using rate and spectral deformation.
**DETECTOR DESIGN**

- **Outer Veto:** plastic scintillator strips
- **Chimney:** deployment of radioactive source for calibration in the $\nu$-Target and $\gamma$-Catcher.
- **$\nu$-Target:** 10.3 m$^3$ scintillator (PXE based) doped with 1g/l of Gd in an acrylic vessel (8 mm)
- **$\gamma$-Catcher:** 22.5 m$^3$ scintillator (PXE based) in an acrylic vessel (12 mm)
- **Buffer:** 100 m$^3$ of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 inches)
- **Inner Veto:** 90 m$^3$ of scintillator (LAB based) in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)
- **Shielding:** about 250 t steel shielding (150 mm) (FD) / 1 m water (ND)
**Accidental BG**

- Radioactivity from materials, PMTs, surrounding rock ($^{208}$Tl).

**Correlated BG**

- Fast neutrons
  - Neutrons from cosmic $\mu$ spallation gives recoil protons (low energy).
- Stopping $\mu$
  - Cosmic $\mu$ entering from the chimney.
- Cosmogenics
  - Electrons from $^9$Li/$^8$He $\beta + n$ decays.

**Prompt**

- Neutrons from cosmic $\mu$ spallation captured on Gd/H, or $\gamma$ like prompt fake signal in case of H analysis.

**Delay**

- Neutrons from cosmic $\mu$ spallation captured on Gd/H, or $\gamma$ like prompt fake signal in case of H analysis.

- Michel electrons.

- Neutrons from $^9$Li/$^8$He $\beta + n$ decays captured on Gd/H.
Double Chooz SETUPS

- 2 reactor cores and 2 detectors.
- Unique DC features: almost iso-flux setup, reactor-off data (~7 days).
- 2 phases:
  - Single Detector (SD) period: ~480 days (FD1-only ~2011)
  - Multi Detector (MD) period: ~350 days (FDII +ND ~ 2015)
- Bugey4 anchor: Bugey4 experimental result is used as virtual ND.
Double Chooz MILESTONES (single detector)

**MILESTONES (single detector)**

- **First indication of non-zero $\theta_{13}$ and rate+shape analysis**
  

- **First n-H capture analysis**
  

- **First (and only) Reactor Rate Modulation (RRM) analysis**
  
  *Phys.Lett. B735 (2014) 51-56*

- **First publication on “5 MeV distortion”**
  
  *JHEP 1410 (2014) 86*

**Multi-detector results:**

- First multi-detector results on n+Gd released at Moriond 2016.

- New results with higher statistics and larger neutrino target released in September 2016.
STATISTICS: AN ISSUE?

- The result presented at Moriond 2016 were dominated by the statistic.

- The projection of the uncertainty on $\theta_{13}$ shows that statistics is the limiting factor for about 10 years.

- Exploiting the Gamma Catcher as neutrino target, Double Chooz is no longer dominated by the statistics.
50 events per day at FD
σ_{stat} = 0.56%

140 events per day at FD
σ_{stat} = 0.35%
The signal selection follows the same strategy as for Gd analysis but the background rejection is more demanding.

A Neural Network (ANN), based on $\Delta R$, $\Delta t$ and on the delayed energy, is used to reduce the accidental background.

### Neutrino candidates selection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt Energy</td>
<td>1 - 20 MeV</td>
</tr>
<tr>
<td>Delayed Energy</td>
<td>1.3 - 10 MeV</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>0.5 - 800 $\mu$s</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>&lt; 1.2 m</td>
</tr>
<tr>
<td>Isolation window (prompt)</td>
<td>[-800, +900] $\mu$s</td>
</tr>
<tr>
<td>$\Delta t$ after a muon</td>
<td>&gt; 1250 $\mu$s</td>
</tr>
</tbody>
</table>
In the IBD selection there are background contributions which are efficiently removed by the use of several vetoes.

**BG after all vetoes [0.5,20] MeV**

<table>
<thead>
<tr>
<th></th>
<th>FD</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBD prediction (day⁻¹)</td>
<td>~110</td>
<td>~780</td>
</tr>
<tr>
<td>⁹Li (day⁻¹)</td>
<td>~2.5</td>
<td>~11</td>
</tr>
<tr>
<td>Correlated BG (day⁻¹)</td>
<td>~2.5</td>
<td>~21</td>
</tr>
<tr>
<td>Accidental BG (day⁻¹)</td>
<td>~4</td>
<td>~3</td>
</tr>
</tbody>
</table>
ND PERFORMANCE

• The ND response is very similar to the FD one and fulfils the expectations.

• For example in the Cf calibration campaign (same source for the two detectors) we obtained a relative response linearity $\leq 0.3\%$ within $[1,10]$ MeV.

• However we had a leak issue: some Gd in Gamma Catcher and some scintillator in Buffer.

• Gd in the GC is not an issue in the Gd+H analysis (self compensating).

• The scintillator in the Buffer is an issue for stopping muons which are already a factor of 100 higher in ND with respect to FD.

Not an issue after background rejection
ENERGY SPECTRA

FD-I
~ 40k IBD

FD-II
~ 40k IBD

ND
~ 200k IBD
FIT AND RESULT

- The fit is done comparing FD-I, FD-II and ND data to the Monte Carlo (prediction + BG).
- Correlation of systematics errors are included in the fit as well as energy non linearities.
- BG rate and shapes are estimated by data (Li BG rate is not constrained in the fit and only shape information is used).

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

<table>
<thead>
<tr>
<th>Background</th>
<th>Estimation FD</th>
<th>Fit output FD</th>
<th>Estimation ND</th>
<th>Fit output ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9$Li ($\beta$-n)</td>
<td>2.59 ± 0.61</td>
<td>2.55 ± 0.23</td>
<td>11.11 ± 2.96</td>
<td>14.4 ± 1.2</td>
</tr>
<tr>
<td>Correlated</td>
<td>2.54 ± 0.10</td>
<td>2.51 ± 0.05</td>
<td>20.77 ± 0.43</td>
<td>20.85 ± 0.31</td>
</tr>
</tbody>
</table>
CROSS CHECK

- As a cross check we performed a data-data fit using ND and FD-II.
- This is not affected by the MC spectrum distortion between [4,6] MeV.
- The obtained result is in agreement with the one from the data/MC fit using all the available statistics.

\[
\sin^2(2\theta_{13})^{R+S} = (0.123 \pm 0.023) \\
\chi^2 / \text{ndf: } 10.6 / 38
\]
**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** \( \theta_{13} \) is higher than other \( \theta_{13} \) reactor values (by \( \sim 2.2\sigma \) wrt Data Bay).

- The \( \theta_{13} \) value is a key parameter for future CP-violation and mass hierarchy experiments.
• With the multi detector analysis (Gd+H) the statistics is no more a limiting factor.

• The largest systematics comes from detection systematics: the uncertainty on the proton number in the GC limits the sensitivity to 0.76% whereas if we consider only the neutrino target the detection systematics is 0.3%.

• With a reduction on the proton number uncertainty we could reach a sensitivity $\leq 0.01$ (work in progress).
CONCLUSIONS

• Double Chooz has released a measurement of mixing angle $\theta_{13}$ exploiting the multi detector analysis: $\sin^2(2\theta_{13}) = 0.119 \pm 0.016$.

• The use of all neutron captured (Gd+H) allowed for an increase of statistics (statistical error reduce by 40%) which was the limiting factor.

• The new analysis allowed to correctly take into account the (tiny) leak between Target and Gamma Catcher.

• The reactor flux uncertainty is strongly suppressed thanks to the almost iso-flux geometry (<0.1%).

• We are today dominated by the proton number uncertainty: work is in progress to reduce it and a final sensitivity better than 0.01 on $\sin^2(2\theta_{13})$ could be achieved.
THE COLLABORATION

- **France:**
  CEA/IRFU SPP & SPhN & SEDI & SIS & SENAC Saclay, APC Paris, Subatech Nantes, IPHC Strasbourg

- **Germany:**
  MPIK Heidelberg, TU München, EKU Tübingen, RWTH Aachen

- **Japan:**

- **Russia:**
  RAS, Kurchatov Institute (Moscow)

- **Spain:**
  CIEMAT Madrid

- **USA:**
  Alabama, ANL, Chicago, Columbia, Drexel, Kansas State, MIT, Notre Dame, Tennessee, IIT, U.C. Davis, Virginia Tech

- **Brazil:**
  CBPF, UNICAMP, UFABC