Multi-detector results from the Double Chooz experiment

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On Behalf of the Double Chooz Collaboration

Moriond - 24th March 2017
INTRODUCTION (1)

- 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:

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

- 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: $\mathcal{O} \left( \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right)$. 
INTRODUCTION (2)

• The reactor measurement is **complementary** with respect to the long baseline oscillation experiments.

• The combination of the two results in hints of maximal CP violation.

Marrone et al. - Neutrino2016
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:

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

The survival probability depends on \( E_{\nu_e} \) 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)
**BACKGROUND**

### Accidental BG
- **Prompt**: Radioactivity from materials, PMTs, surrounding rock ($^{208}\text{TI}$).
- **Delay**: Neutrons from cosmic $\mu$ spallation captured on Gd/H, or $\gamma$ like prompt fake signal in case of H analysis.

### 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 $^{9}\text{Li}/^{8}\text{He}$ $\beta + n$ decays.

**Cosmic $\mu$ entering from the chimney.**

**Recoil p**

**Gd**

**$^{9}\text{Li,}^{8}\text{He}$**

**$^{12}\text{C}$**
Double Chooz MILESTONES (single detector)

Multidetector results:

- First multidetector 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.

![Graph showing the projection of the uncertainty on $\theta_{13}$ over time.](image)
50 events per day at FD
\( \sigma_{\text{stat}} = 0.56\% \)

140 events per day at FD
\( \sigma_{\text{stat}} = 0.35\% \)
**SELECTION**

- 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.

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### Neutrino candidates selection

<table>
<thead>
<tr>
<th></th>
<th>Prompt Energy</th>
<th>Delayed Energy</th>
<th>$\Delta t$</th>
<th>$\Delta R$</th>
<th>Isolation window (prompt)</th>
<th>$\Delta t$ after a muon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 - 20 MeV</td>
<td>1.3 - 10 MeV</td>
<td>0.5 - 800 $\mu$s</td>
<td>&lt; 1.2 m</td>
<td>[-800, +900] $\mu$s</td>
<td>&gt; 1250 $\mu$s</td>
</tr>
</tbody>
</table>

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**ND delayed**

<table>
<thead>
<tr>
<th>Before ANN</th>
<th>After ANN</th>
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</table>

**ND prompt**

<table>
<thead>
<tr>
<th>Before ANN</th>
<th>After ANN</th>
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</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 detector) 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.
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)

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

<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.

\[ \sin^2(2\theta_{13})^{R+S} = (0.123 \pm 0.023) \]
\[ \chi^2 / \text{ndf: 10.6 / 38} \]
EXTRAPOLATION

• 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).

![Graph showing DC sensitivity evolution for Gd+H analysis](image)
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