Measurement of the $\theta_{13}$ neutrino mixing angle with the two detectors of the Double Chooz experiment

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### Status on Neutrino Oscillation Knowledge

- Standard Model (3 families)
- PMNS$_{3\times3}$ ($\theta_{12}, \theta_{23}, \theta_{13} + 1 \delta_{\text{CP}}$ phase)
- Two independent square mass differences $\pm \Delta m^2, \delta m^2$

#### PMNS Matrix

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>NuFIT 5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{12}$</td>
<td>SNO+SK</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>NOνA</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>Reactor exp</td>
</tr>
<tr>
<td>$\Delta m^2$</td>
<td>KamLAND</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2</td>
</tr>
<tr>
<td>Sign $\Delta m^2$</td>
<td>unknown</td>
</tr>
<tr>
<td>CPV</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Must measure all parameters with high precision

Characterise & test (i.e. over-constrain) Standard Model

$\theta_{13}$ CANNOT BE MEASURED BY OTHERS THAN REACTOR EXPERIMENTS!
Status of $\theta_{13}$

Reactor-$\theta_{13}$ experiments
Double Chooz $\oplus$ Daya Bay $\oplus$ RENO

Challenges:

- Statistics: $\sim 10^5$ (far) $< 10^6$
- Systematics: order of 0.1% (each)
  - Detection
  - Flux
  - BG
- Energy control: <1% precision
The Double Chooz site

**NEAR DETECTOR**
L = 400 m  120 m.w.e
~ 800 ν/day
(Dec 2014 – Dec 2017)

**FAR DETECTOR**
L = 1050 m  300 m.w.e
~ 100 ν/day
(April 2011 – Dec 2017)

Antineutrinos are produced in nuclear reactors by the β-decay of the fission products:

\[ {\bar \nu}_e \text{ disappearance is directly related with } \theta_{13} \]

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

\[ {\bar \nu}_e \text{ survival probability} \]

CNPE Chooz
2 x 4.27 GWth
10^21 ν/s

\[ ^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu} \]
**Inverse β decay**

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

- **Prompt signal**
  
  Energy losses + \( e^+ \) annihilation
  
  \[ E(\text{prompt}) \approx E(\bar{\nu}_e) - 0.8 \text{ MeV} \]

- **Delayed signal**
  
  Neutron capture on **Gadolinium** (Gd), emission of 8 MeV γ rays
  
  * Alternatively, \( n \)-capture on **Hydrogen** (H) (~2.2 MeV)

\[ Gd \quad \sim 30 \mu s \quad 8 \text{ MeV} \]

\[ H \quad \sim 200 \mu s \quad 2.2 \text{ MeV} \]
The Double Chooz Detectors

Far detector

\( v \)-catcher

\( v \)-target

Near detector

Smallest \( v \)-target \( \theta_{13} \) reactor experiments
New Data

Nature Physics Data Set (+1.5y of Far only data)

Extra set included in this talk

Far Detector
\[ \sim 150 \nu/\text{day} \]

Near Detector
\[ \sim 1000 \nu/\text{day} \]

Reactor
Thermal Power

2 REACTORS OFF
Motivation for the TnC technique

Statistics is limiting factor in the sensitivity of $\theta_{13}$

- Major increase of the detection volume
  - Increase of signal statistics by more than a factor of 2.5 (Gd-only)

Small Gd-target (8.3 t) vs. Gd+H+C-target (~30 t)

- Neutron capture efficiency
- Delayed energy window maximally open
- Large Gamma Catcher proton number uncertainty ~0.6%
Challenge: control of larger BGs

Reduced by 3 orders of magnitude!
**Better Constraint of Cosmogenic BG**

- **Double Chooz Preliminary**
  - Near (587 live-days)
  - Far (1276 live-days)

- **9Li** Rate uncertainty 7%
- Fast-neutron Rate uncertainty 1%
- Accidental Rate uncertainty < 1%

- Help to further constraint the FN rate
- Data driven spectra (model)
### Reactors OFF data

**Direct measurement of the backgrounds**

**Background understanding**

<table>
<thead>
<tr>
<th></th>
<th>Events/day FD</th>
<th>Events/day ND</th>
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</thead>
<tbody>
<tr>
<td>OFF-OFF (2012)</td>
<td>8.9 ± 1.2</td>
<td>---</td>
</tr>
<tr>
<td>OFF-OFF (2017)</td>
<td>9.8 ± 0.9</td>
<td>39.6 ± 2.5</td>
</tr>
<tr>
<td>BG estimated (fit)</td>
<td>9.3 ± 0.3</td>
<td>38.5 ± 1.5</td>
</tr>
</tbody>
</table>

Good agreement, all numbers within 1σ

Acc + FN + Li³

- ~7 days of 2-Off data (only FD working)
- ~23 days of 2-Off data (FD & ND)

### Shape info used for first time in the Rate+Shape $\theta_{13}$ fit

- New Reactor-off Data gives extra constrains on BG above 3 MeV
**Major cancellation of reactor flux**

**Isoflux configuration**

- Relative contribution by each reactor to the total detected $\bar{\nu}_e$ flux is almost the same for both detectors. The ND becomes an effective monitor of the FD.
- Reactor flux error highly suppressed with multi-detectors.
Positron Energy Model

- More Data allowed:
  - Better understanding of detector stability & uniformity
- Dedicated calibration campaigns allowed:
  - Extra constrain of light & charge non-linearities
- Energy controlled ~0.5% in $\theta_{13}$ region

![MC Energy Correction vs. Visible Energy](image1)

![Energy Scale Uncertainty](image2)

Input for $\theta_{13}$ fit
\[ \sin^2(2\theta_{13}) = 0.102 \pm 0.012 \]

(stable result also for Rate or Shape only analysis)

**θ_{13} Rate+Shape Oscillation fit**

**Inter-detector ratio**

(reactor model cancellation)
Systematics Breakdown

DC-IV [Nature Physics]

DC-V PRELIMINARY

THIS TALK

- Flux: 0.0062, 23%
- Detection [proton#]: 0.0073, 12%
- Background: 0.0018, 28%
- Energy: 0.0018, 50%
- Δm2: 0.0018, 5%
- Statistics: 0.0054, 18%
- Correlation: 0.0064, 8%

~0.1% (isoflux ND:FD)
~0.2% ?? (if new GC p# unc to v-target unc)
Mean cross-section per fission

\[ N_v^{\exp}(t) \propto \epsilon \frac{N_p}{L_R^2} \frac{P_R^{\text{th}}}{\langle E_f \rangle_R} \langle \sigma_f \rangle_R \]

Best Integral Flux Measurement to Date

EXCELLENT AGREEMENT WITH BUGEY4 AND DAYA BAY

DC ND Fission fraction (2 reactors weighted)

\( ^{235}\text{U} \rightarrow 0.520 \)
\( ^{238}\text{U} \rightarrow 0.087 \)
\( ^{239}\text{Pu} \rightarrow 0.333 \)
\( ^{241}\text{Pu} \rightarrow 0.060 \)

(*) Results before Neutrino 2018
**Propects and Conclusions**

- **Extra statistics →** Better bkg constraint, detection systematics, flux cancellation and stability
- **Reactor off →** Better bkg constraint
- **Improved energy systematics**
- **New result:** $\sin^2(2\theta_{13}) = 0.102 \pm 0.012$ (w/ full two detectors data)

- Detector dismantling underway. Goal: a better GC proton number measurement
- Still room for $\sin^2(2\theta_{13})$ improvement ($1\sigma \leq 0.01$)
Thank you!

97 scientists 25 institutions (Americas, Asia, Europe)

doublechooz.in2p3.fr