Status of Double Chooz Reactor Neutrino Oscillation Experiment

Zelimir Djurcic
Physics Department
Columbia University

Implications of Neutrino Flavor Oscillations Workshop
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Neutrino Oscillation Results

Missing information:

1. What is $\nu_e$ component in the $\nu_3$ mass eigenstate?
   - The size of the “little mixing angle”, $\theta_{13}$?
     - Only know $\theta_{13} < 13^\circ$

2. Is the $\mu - \tau$ mixing maximal?
   - $35^\circ < \theta_{23} < 55^\circ$

3. What is the mass hierarchy?
   - Is the solar pair the most massive or not?

4. What is the absolute mass scale for neutrinos?
   - We only know $\Delta m^2$ values

5. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?

Lot’s of questions but the Big Question is “How big is the the little mixing angle $\theta_{13}$?”
Experimental Methods to Measure $\Theta_{13}$

- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.4 \times 10^{-3}$ eV$^2$
  - Look for appearance of $\nu_e$ in a pure $\nu_\mu$ beam vs. $L$ and $E$
  - Use near detector to measure background $\nu_e$'s (beam and misid)

  **NOvA:**
  $\langle E_\nu \rangle = 2.3$ GeV
  $L = 810$ km

  **T2K:**
  $\langle E_\nu \rangle = 0.7$ GeV
  $L = 295$ km

- Reactors: Disappearance ($\overline{\nu}_e \rightarrow \overline{\nu}_e$) at $\Delta m^2 \approx 2.4 \times 10^{-3}$ eV$^2$
  - Look for a change in $\overline{\nu}_e$ flux as a function of $L$ and $E$
  - Look for a non- $1/r^2$ behavior of the $\nu_e$ rate
  - Use near detector to measure the un-oscillated flux

  **Double Chooz:**
  $\langle E_\nu \rangle = 3.5$ MeV
  $L = 1100$ m
Oscillation probability complicated and dependent not only on $\theta_{13}$ but also:

1. CP violation parameter ($\delta$)

\[
P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 (\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2
\]

2. Mass hierarchy (sign of $\Delta m_{31}^2$)

\[
+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 (aL)}{(aL)^2} \Delta_{21}^2
\]

3. Size of $\sin^2 \theta_{23}$

\[
+ \cos \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos \Delta_{32} \left( \frac{\sin (\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31} \right) \left( \frac{\sin (aL)}{(aL)^2} \Delta_{21} \right)
\]

\[
+ \sin \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin \Delta_{32} \left( \frac{\sin (\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31} \right) \left( \frac{\sin (aL)}{(aL)^2} \Delta_{21} \right)
\]

$\Rightarrow$ These extra dependencies are both a “curse” and a “blessing” since they will let us measure CP violation if $\theta_{13}$ is big enough.
Accelerator vs Reactor Experiment

Reactor Disappearance Experiments

$\theta_{13}$ probed by measuring the disappearance of reactor produced electron antineutrinos.

Need to work at an L/E matched to the atmospheric $\Delta m^2$
(C.F. Kamland measurement at solar $\Delta m^2$)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

$$- \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

$\Delta_{ij} = 1.27 \Delta m^2_{ij} \frac{L}{E}$

$L$(km), $E$(MeV), $m(10^{-3}eV)$

$\Rightarrow$ Reactor disappearance measurements provide a straight forward method to measure $\theta_{13}$ with no dependence on matter effects and CP violation
Reactors as Anti-neutrino Sources

Use very high flux of $\bar{\nu}_e$ from nuclear power reactors
- Need to know the $\bar{\nu}_e$ flux vs time

Use “inverse beta decay” process to detect $\bar{\nu}_e$ events
$\bar{\nu}_e + p \rightarrow e^+ + n$
- Need to know the cross section vs neutrino energy

Detect the $\nu_e$ flux at two distances from the reactor
- Cancels many systematic uncertainties in flux and detection
- Need to know the exact position of cores and detectors

Minimize systematic uncertainties
- Use two “identical” detectors
- Go underground with well-designed veto system
  ⇒ Reduce cosmic muon backgrounds
Nuclear Reactors as a Source of $\bar{\nu}_e$’s

What creates the reactor $\bar{\nu}_e$’s?

- Typical modern nuclear power reactor has a thermal power of: $P_{\text{therm}} = 3.8$ GW
  - About 200 MeV / fission of energy is released in fission of $^{235}\text{U}$, $^{239}\text{Pu}$, $^{238}\text{U}$, and $^{241}\text{Pu}$.
  - The resulting fission rate, $f$, is thus: $f = 1.2 \times 10^{20}$ fissions/s
  - At 6$\bar{\nu}_e$ / fission the resulting yield is: $7.1 \times 10^{20} \bar{\nu}_e / s$.

Example: $^{235}\text{U}$ fission

$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$

Most likely A from $\Rightarrow ^{94}\text{Zr}^{140}\text{Ce}$

$^{235}\text{U}$ fission

$\rightarrow$ on average 6 n have to $\beta$-decay to 6 p to reach stable matter:

$^{94}\text{Zr}^{140}_{58}\text{Ce}$

$\rightarrow$ on average 1.5 $\nu_e$ are emitted with energy $> 1.8$ MeV

Using $e^-$ spectra measurements for $^{235}\text{U}$, $^{239}\text{Pu}$, and $^{241}\text{Pu}$ Can calculate the $\nu_e$ flux to $\sim 1.5\%$. 
Reactor $\bar{\nu}_e$ Energy Spectrum

- $^{235}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ from $\beta$ measurements
- $^{238}\text{U}$ calculated
- Time dependence due to fuel cycle

- $\sim 200$ MeV per fission
- $\sim 6 \; \bar{\nu}_e$ per fission
- $\sim 2 \times 10^{20} \; \bar{\nu}_e / \text{GW}_\text{th} \cdot \text{sec}$
Detection Technique

• The reaction process is inverse β-decay followed by neutron capture
  – Two part coincidence signal is crucial for background reduction.

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

• Positron energy spectrum implies the neutrino spectrum
  \((e^+e^-\rightarrow \gamma\gamma)\)

\[
E_\nu = E_{\text{vis}} + 1.8 \text{ MeV} - 2m_e
\]

• The scintillator may be doped with gadolinium to enhance capture

\[
n^m\text{Gd} \rightarrow ^{m+1}\text{Gd} \gamma's \ (8 \text{ MeV})
\]

Signal = Positron signal + Neutron signal (within a few capture times)
Detection cross section

\[ \sigma_{tot}(E_e) \approx \frac{2\pi^2 \hbar^3}{m_e^5 c^7 f\tau_n} \cdot p_e \cdot E_e \approx \frac{p_e \cdot E_e}{1 \text{ MeV}^2} \cdot 10^{-43} \text{ cm}^2 \]

In lowest order, assuming infinitely heavy neutron.

No nuclear matrix element involved. Cross section directly linked to measured neutron life time and phase space.

Use cross section by Vogel & Beacom:
\( \sigma \) to order 1/M, radiative corrections, weak magnetism → few % correction

Cross section accurate to 0.2%
$\bar{\nu}_e$ Energy Spectrum

Neutrinos with $E<1.8$ MeV are not detected

$\nu_e + p \rightarrow n + e^+$ cross-section

Calculated reactor $\nu_e$ spectrum
Comparison of Prediction to Observation

Figure 5: Positron spectrum measured at 45.0 m from the core of the Gösgen reactor [36]. Data points are obtained after background subtraction, errors are statistical only. The solid curve is a fit to the data assuming no oscillations. The dashed curve is derived independently by $\beta$-spectroscopy.

Flux and Energy Spectrum known at $\sim$1-2 % level

$\rightarrow$ Reactors are calibrated sources of $\nu$'s
The current best limit for $\sin^2 2\Theta_{13}$ is from the Chooz experiment.

Chooz ran for only 197 days at reduced reactor power.

\[ \text{CHOOZ : } R_{\text{osc}} = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (syst)} \]
**Previous Best Measurement: Chooz Experiment**

- CHOOZ Experiment: current best limit on $\theta_{13}$
  - One detector experiments
    - Major systematic was reactor flux
  - Large singles rate due to radioactivity of PMTs
    - Scintillator out to tubes
  - Some troubles with reactors
    - Only 200 days of data with either reactor on
  - Also, detector stability issues with scintillator
    - Light output decreasing with $\tau=720$ days

- Small fiducial mass:
  - CHOOZ: 5 tons @ 1km, 5.7 GW
    - $\sim$2.2 evts/day/ton with $0.2$-$0.4$ bkgnd evts/day/ton
    - $\sim$3600 $\nu$ events

<table>
<thead>
<tr>
<th>parameter</th>
<th>relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>reaction cross section &amp; flux</td>
<td>1.9%</td>
</tr>
<tr>
<td>number of protons</td>
<td>0.8%</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>1.5%</td>
</tr>
<tr>
<td>reactor power</td>
<td>0.7%</td>
</tr>
<tr>
<td>energy released per fission</td>
<td>0.6%</td>
</tr>
<tr>
<td>combined</td>
<td>2.7%</td>
</tr>
</tbody>
</table>
$\sin^2 2\theta_{13} < 0.19$ at 90% CL (or $\theta_{13} < 13^\circ$)

Previous Best Measurement: Chooz Experiment

Best current limit from:
CHOOZ (single detector experiment)
$\sin^2(2\theta_{13}) < 0.2$
($\sin^2(\theta_{13}) < 0.05$)
Non-zero $\Theta_{13}$ Hint

Recent global analysis fit for $\sin^2\theta_{13}$ vs $\sin^2\Theta_{12}$: Fogli et al.

Best fit: $\sin^22\Theta_{13}=0.06 \pm 0.04$

Is $\Theta_{13}$ non-zero and within a reach?
$\rightarrow$ Need new sensitive experiments to tell
The Double Chooz Collaboration

§ Brasil: CBPF, UNICAMP

§ France: APC - IN2P3, Dapnia CEA/Saclay, Subatech-IN2P3, IPHC-IN2P3, Strasbourg

§ Germany: EKU Tübingen, MPIK Heidelberg, TU München, Aachen, Universität Hamburg

§ Japan: Hiroshima IT, Kobe U, Niigata U, Tohoku U, Tohoku Gakuin U, Tokyo IT, Tokyo Metropolitan U

§ Russia: RAS, Kurchatov Institute (Moscow)

§ Spain: CIEMAT (Madrid)

§ UK: Sussex

§ USA: ANL, Barnard College, U Chicago, Columbia U, Drexel U, IIT, LLNL, MIT, Sandia Labs, U Alabama, UC Davis, U Notre Dame, U Tennessee
The Double Chooz Collaboration

Spokesperson: Herve de Kerret (APC)
Double Chooz Strategy

- Use two identical detectors to remove the leading source of systematic error in CHOOZ: uncertainties on reactor neutrino spectrum
- Drastically reduce other systematic sources by relative measurement

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2 [eV^2] \frac{L [m]}{E [MeV]}) \]
Double Chooz Improvement on Original Chooz

\[ \text{CHOOZ : } R_{\text{osc}} = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (syst)} \]

Double Chooz Goal: \( \pm 0.4\% \text{ (stat.)} \pm 0.6\% \text{ (syst.)} \)

- **Statistics**
  - More powerful reactor (multi-core)
  - Larger detection volume \( \rightarrow \) Double Chooz
  - Longer exposure \( \rightarrow \) Double Chooz

- **Experimental error:** \( \nu \) flux and cross-section uncertainty
  - Multi-detector \( \rightarrow \) Double Chooz
  - Identical detectors to reduce inter-detector systematics (normalization, calibration ...) \( \rightarrow \) Double Chooz

- **Background**
  - Improve detector design \( \rightarrow \) Double Chooz
  - Better cosmic muon veto system \( \rightarrow \) Double Chooz
  - Improve background knowledge by direct measurement \( \rightarrow \) Double Chooz
Chooz Power Plant

Two reactor cores: 4.27 GW_{th} / core
The Double Chooz Site in Ardennes (France)
Double Chooz Detector Components

Outer Muon Veto (panels of strips of coextruded plastic scintillator) tag near passing muons causing fast-ne.

Target

\[ \text{v interaction volume} \]

- acrylic vessel (th=8mm)
- Liquid Scint.
- 10.1m\(^3\) doped 0.1% Gd

Muon Inner Veto

tag traversing muons and fast-ne

- stainless steel vessel (th=10mm)
- 80m\(^3\) Liquid Scint. (78 8" PMTs)

Shielding

reduce radioactivity from the rock

- steel (th=150mm)

Gamma Catcher

catch exiting \( \gamma \) energy

- acrylic vessel (th=12mm)
- 22.6m\(^3\) Liquid Scint.

Buffer

isolate PMT from target reducing singles bk.

- stainless steel vessel (th=3mm)
- 114.2m\(^3\) mineral oil
- 390 PMT (10 inch)
Backgrounds

Backgrounds to the $e^+ - n$ coincidence signal

**Uncorrelated Backgrounds**
- accidentals
- cosmogenic neutrons

**Correlated Backgrounds**
- muon produced fast neutrons in the surrounding rock and shielding
- muon produced radioactive nuclei that emit an electron and neutron
  eg. $^9\text{Li}$ (T1/2=178ms)
Outer Veto System

- Reduce muon produced spallation neutron rate (x5)
- Track muons that capture in dead material and produce neutrons
- Tag muons that can produce $^9$Li background
Outer Veto System

OV design for near detector consists of upper and lower tracking planes.

Each plane is fully active and consists of modules oriented in both X and Y directions.

OV modules consist of 2 layers of 64 scintillator strips with WLS fibers connected to a multi-anode PMT.

Full-scale OV module prototype.
# Effect of Veto on Observed Backgrounds

## No Veto System

<table>
<thead>
<tr>
<th>Detector</th>
<th>Site</th>
<th>Accidental Rate ( (d^{-1}) )</th>
<th>Background</th>
<th>Correlated ( \mu )-Capture</th>
<th>(^9\text{Li} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>Far</td>
<td>0.5 ± 0.3</td>
<td>1.5 ± 0.8</td>
<td>2.0 ± 2.0</td>
<td>28</td>
</tr>
<tr>
<td>(69 ( \nu /d ))</td>
<td></td>
<td>0.7%</td>
<td>2.2%</td>
<td>2.9%</td>
<td>40%</td>
</tr>
</tbody>
</table>

## With Inner and Outer Veto System

<table>
<thead>
<tr>
<th>Detector</th>
<th>Site</th>
<th>Accidental Rate ( (d^{-1}) )</th>
<th>Background</th>
<th>Correlated ( \mu )-Capture</th>
<th>(^9\text{Li} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>Far</td>
<td>0.1 ± 0.1</td>
<td>0.3 ± 0.2</td>
<td>0.11 ± 0.11</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>(69 ( \nu /d ))</td>
<td></td>
<td>0.1%</td>
<td>0.4%</td>
<td>0.2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>systematics &lt;0.1%</td>
<td>&lt;0.1%</td>
<td>0.2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>Near</td>
<td>0.5 ± 0.3</td>
<td>1.7 ± 0.9</td>
<td>0.15 ± 0.15</td>
<td>0.4</td>
</tr>
<tr>
<td>(1012 ( \nu /d ))</td>
<td></td>
<td>&lt;0.1%</td>
<td>0.2%</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>systematics &lt;0.1%</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>
Liquid Scintillator

- Target scintillator composed of 20% PXE, 80% Dodecane, PPO, Bis-MSB, Gd(dpm)$_3$
  - Good stability tested over 3 years
  - Attenuation length >10m @ 430 nm
  - Materials exposed to the target are tested for compatibility
  - 0.1% Gd loading
  - Light yield ~ 7000 ph/MeV

- Gamma Catcher Scintillator composed of 4% PXE, 46% Dodecane, 50% oil, PPO, Bis-MSB
  - Density and light yield matched to the target

- Inner Veto filled with scintillating LAB oil
Inner Detector Phototubes

- 10” Ultra low background tubes
- 390 PMTs
  (270 side, 120 top + bottom)
- 13 % coverage
- Energy resolution goal:
  7% at 1 MeV

- Readout FEE: gain x15, pulse shape, trigger = analog sum>0.4MeV
- FADC, 500MHz, 8bit
- No deadtime
- Special muon showering electronics
Calibration

- Relative near/far detection uncertainty goal <0.6%
  - energy cut at threshold <0.1%
  - energy cut at 6 MeV for neutron capture <0.2%
  - neutron capture time distribution <0.1%
  - deadtime <0.1%
  - spatial cut (if used) <0.2%

Calibration source deployment - $\gamma$, n, $\beta$

- Guide tubes inside detector
- z-axis system
- articulated arm
- Embedded LEDs
Calibration Sources

- Gamma Sources ($^{203}$Hg, $^{137}$Cs, $^{68}$Ge, $^{60}$C, PoC).
  - Calibrates the energy scale, light transport, PMT QE, timing, deadtime, and detector stability

- Neutron Sources (PoC, $^{252}$Cf, AmBe)
  - Calibrates the energy scale, n-detection efficiency and deadtime

- Light Flasher (multi-wavelength laser system, multi-wavelength LED system)
  - Calibrates the light transport, PMT gain and efficiency and detector stability

- Cosmics (muons, spallation neutrons, cosmogenics)
  - Calibrates the energy scale, PMT gain, and detector stability
Analysis Cuts

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

- Previous Chooz: 1.5% syst. err.
  - 7 analysis cuts
- Goal Double-Chooz: \(~0.3\%\) syst.
  - 3 analysis cuts
  1. \(e^+\) annihilation energy > 0.4 MeV
  2. neutron capture energy > 6 MeV
  3. \(\Delta t(e^+ - n) < 100 \mu\text{sec}\)

<table>
<thead>
<tr>
<th>Selection Cut</th>
<th>CHOOZ rel. error (%)</th>
<th>Double-CHOOZ rel. error (%)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>positron energy*</td>
<td>0.8</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>positron-geode distance</td>
<td>0.1</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>neutron capture</td>
<td>1.0</td>
<td>0.2</td>
<td>Cf calibration</td>
</tr>
<tr>
<td>capture energy containment</td>
<td>0.4</td>
<td>0.2</td>
<td>Energy calibration</td>
</tr>
<tr>
<td>neutron-geode distance</td>
<td>0.1</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>neutron delay</td>
<td>0.4</td>
<td>0.1</td>
<td>—</td>
</tr>
<tr>
<td>positron-neutron distance</td>
<td>0.3</td>
<td>0 – 0.2</td>
<td>0 if not used</td>
</tr>
<tr>
<td>neutron multiplicity*</td>
<td>0.5</td>
<td>0</td>
<td>not used</td>
</tr>
<tr>
<td>combined*</td>
<td>1.5</td>
<td>0.2-0.3</td>
<td>—</td>
</tr>
</tbody>
</table>

*average values
Example Measurement (Double Chooz 3 Years)

\[
\sin^2(2\theta_{13}) = 0.1 \quad \text{and} \quad \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2
\]
## Double Chooz Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Chooz</th>
<th>Double-Chooz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor-induced</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ν flux and σ</td>
<td>1.9 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Reactor power</td>
<td>0.7 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Energy per fission</td>
<td>0.6 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Two “identical” detectors, Low bkg</td>
</tr>
<tr>
<td><strong>Detector-induced</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid angle</td>
<td>0.3 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Volume</td>
<td>0.3 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Density</td>
<td>0.3 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>H/C ratio &amp; Gd concentration</td>
<td>1.2 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Spatial effects</td>
<td>1.0 %</td>
<td>&lt;0.1 %</td>
</tr>
<tr>
<td>Live time</td>
<td>-----</td>
<td>0.1 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Special electronic systems and monitoring</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From 7 to 3 cuts</td>
<td>1.5 %</td>
<td>0.2 - 0.3 %</td>
</tr>
<tr>
<td>Total</td>
<td>2.7 %</td>
<td>&lt; 0.6 %</td>
</tr>
</tbody>
</table>
DC improvements respect to CHOOZ

**Increased statistics:**
- Longer exposure
- Larger detector mass

**Reduced systematic uncertainties**
- Near/Far detectors comparison to minimize reactor errors
- Identical detector to do relative measurements
- Detailed calibration program

**Suppressed background**
- Improved detector design
- Better cosmic muon veto detectors
- Better external shielding

<table>
<thead>
<tr>
<th></th>
<th>CHOOZ</th>
<th>DOUBLE CHOOZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target volume</td>
<td>5.55 m³</td>
<td>10.3 m³</td>
</tr>
<tr>
<td>Target composition</td>
<td>6.77 E28 H/m³</td>
<td>6.55 E28 H/m³</td>
</tr>
<tr>
<td>Data taking period</td>
<td>few months</td>
<td>3-5 years</td>
</tr>
<tr>
<td>Event rate near det.</td>
<td>/</td>
<td>~1 106 / 3 y</td>
</tr>
<tr>
<td>Event rate far det.</td>
<td>2700</td>
<td>40000/3 years</td>
</tr>
<tr>
<td>Statistical error</td>
<td>2.8%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CHOOZ</th>
<th>DOUBLE CHOOZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Cross section</td>
<td>1.9%</td>
<td>/</td>
</tr>
<tr>
<td>Number of protons</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Detector efficiency</td>
<td>1.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Reactor power</td>
<td>0.7%</td>
<td>/</td>
</tr>
<tr>
<td>Energy per fission</td>
<td>0.6%</td>
<td>/</td>
</tr>
</tbody>
</table>

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<tr>
<th></th>
<th>signal</th>
<th>Corr. background</th>
<th>Acc. Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near detector</td>
<td>218 ev./d</td>
<td>11 ev./d</td>
<td>14 ev./d</td>
</tr>
<tr>
<td>Far detector</td>
<td>40 ev./d</td>
<td>2 ev./d</td>
<td>2 ev./d</td>
</tr>
</tbody>
</table>
Double Chooz Sensitivity to $\Theta_{13}$

Double Chooz: sensitivity limit versus year

- Phase I: 1.5 y with the far detector (1.05 km) only
- Phase II: 3.5 y with both near (400 m) and far detectors

Atmospheric mass splitting = 2.5e-3 ev^2

Limit 90% C.L.

Exposure time in years

FAR only

FAR and NEAR
Far and Near Site Status

**Far lab:**
- Tunnel: 200 meters @10%
- New ventilation, doors, safety, …
- Liquid storage building
  - Being upgraded
  - First liquids in summer
    (Veto/Buffer)
- Neutrino laboratory:
  - 1 km baseline (15000 y⁻¹)
  - 300 m.w.e., μ-Rate: ~20 Hz
  - Fire security, Pit refurnished
  - Steel tank installed
  - Lab cleaned and painted (Dec 2009)
  - Muon Veto PMTs installed (February 2009)
  - Buffer Vessel installed (April 2009)
  - Thermalization system installed (April 2009)
  - Inner PMT installation (June 2009)
  - Future/Ongoing: Acrylic tanks, filling liquids, electronics…

**Near lab:**
- EDF committed to digging the near lab
  (November 2008)

Neutrinos are close!
Far Detector Construction

June 08: starting of the work

September 08: the steel shielding.

November 08: the inner veto tank

Dec 08 - Jan 09: painting and cleaning
Far Detector Construction

February 09: the inner veto cleaning

Inner veto PMT mounting

ISO6 tent mounting

Buffer tank installation
Inner Veto PMTs

Inner Veto PMT

Cable routing flange
Buffer Tank Installation
Inner PMTs, June 22
Inner PMTs
Near Detector Status

May 20: the agreement for the Near laboratory have been signed. This was organized by the region Champagne Ardenne. The agreement links this region, Edf, and French agencies.

Site has been chosen with >45m overburden, almost flat topology.

**Near Detector Status**

May 20: the agreement for the Near laboratory have been signed. This was organized by the region Champagne Ardenne. The agreement links this region, Edf, and French agencies.
May 27th:
EdF paper: quite friendly, with a good feeling about the Edf involvement in the experiment.
Schedule

- Conceptual Design Review October, 2006
- Far Lab start assembly, Fall 2007
- Far Lab: shielding installed, June 2008
- Far Lab: inner PMTs installed, June 2008
- Far Lab: target acrylic vessel gluing started
- Far Lab: LS filling to be completed Feb 2010
- Far Detector running Feb 2010
- Far Lab: Outer Veto to be installed April 2010
- Near Lab begin digging Mid 2009
- Near Lab finish digging End 2009
- Near Lab start assembly after digging
- Near Lab finish assembly 2010
Summary

• A new experimental concept to measure the mixing angle $\theta_{13}$
  $\rightarrow$ use nuclear reactors with two identical detectors
  – Double Chooz will be the first of a new generation of neutrino experiments based on this concept

• Several detector improvements are being implemented
  – Stable Gd-loaded scintillators
  – Multi-layer detector design
  – Improved veto and calibration system to reduce systematic uncertainties

• It’s all coming soon !
  – Early 2010: start data taking with far detector
  – 2011: start data taking with near+far
  – 2013: reach sensitivity $\sin^2 2\theta_{13} \sim 0.02$ to 0.03