Review of the site situation for a novel reactor experiment in France for the last undetermined mixing angle $\theta_{13}$

Thierry Lasserre
CEA/Saclay
Low Energy Neutrino Workshop
Munich, October 9 2003
College de France & APC

O. Dadoun, H. De Kerret, D. Kryn, G. Mention, M. Obolensky, S. Sukhotin, D. Vignaud

CEA/Saclay

M. Cribier (& APC), F. Desages-Ardelier, J.P. Meyer, A. Milsztajn, T.L.
Talk1: Review of the site status (T.L.)

Talk2: Systematics uncertainties & Backgrounds for Double-CHOOZ experiment (H. De Kerret)

Talk3: Impact of the systematics on the sensitivity to $\sin^2(2\theta_{13})$ (G. Mention)
**Best current constraint: CHOOZ**

$$\bar{\nu}_e \rightarrow \nu_x$$

- Disappearance experiment
  - $P_{th} = 8.5 \text{ GW}_{th}$, $L = 1.1 \text{ km}$, $M = 5t$
  - Overburden: 300 mwe

- $R = 1.01 \pm 2.8\% \text{(stat)} \pm 2.7\% \text{(syst)}$

- World best constraint!
  - $\Delta m^2_{atm} = 2.10^{-3} \text{ eV}^2$
  - $\sin^2 2\theta_{13} < 0.2$
    - (90% C.L)

One nuclear plant & two detectors

- One nuclear plant
- Two detectors
- Near detector: $D_1 = 0-1$ km
- Far detector: $D_2 = 1-2$ km

Nuclear reactor

- 1,2 core(s) ⇒ ON/OFF: ok
- 4 cores ⇒ ON/OFF: no!

Near detector

- 5-30 tons
- > 50 mwe

Far detector

- 5-30 tons
- > 200 mwe

- Isotrope $\nu_e$ flux (uranium & plutonium fission fragments)
- Detection tag: $\bar{\nu}_e + p \rightarrow e^+ + n$, $<E> \sim 4$ MeV, Threshold $\sim 1.8$ MeV
- Disappearance experiment: suppression+shape distortion between the 2 detectors
- 2 IDENTICAL detectors (CHOOZ, KamLAND, BOREXINO/CTF type):
  - Minimise the uncertainties on reactor flux & spectrum (2 % in CHOOZ)
  - Cancel cross section uncertainty (1.9 %)
  - Challenge: relative normalisation between the two detectors < 1%!
Which site for the experiment?

One reactor complex
Two underground cavities @0.1-1 km & ~1-2 km
The Penly site (Haute Normandie)

<table>
<thead>
<tr>
<th></th>
<th>Penly</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>REP</td>
</tr>
<tr>
<td><strong>Cores</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>$8.3, GW_{th}$</td>
</tr>
<tr>
<td><strong>Coupling</strong></td>
<td>1990-92</td>
</tr>
<tr>
<td><strong>Manufacturer</strong></td>
<td>Framatome</td>
</tr>
<tr>
<td><strong>Operator</strong></td>
<td>EDF</td>
</tr>
</tbody>
</table>
French Nuclear Power Plants

French sites under study

- Nuclear plants embedded in chalk cliff
  Near and Far sites candidates

- Around: La Loire
  Flat topography all around the power plants (vut no detail check ...)

- Around: La Garonne
  Flat topography

- Flat topography
  $H = 0$ meter

- CHOOZ
  Close site OK?
  Problem for the far site?

- Very flat topography, but a lot's of space

- Small cliff at 2km from the reactors, but problem to find the near site

- Around: Le Rhone
  Problem to find a near site close to the river
  Near site swampy
  St Alban: Far site OK?

- Cruas is interesting because the far site is well shielded
  $h \sim 300$ m rocks
Penly: possible detector locations?

- Near site: $D<0.4$ km, shallow overburden $\sim 200$ mwe
- Far site: $D\sim 1.5$ km, shallow overburden $\sim 200$ mwe
Penly: possible detector locations?

Near site
D < 0.4 km

Acces to the far site

Far site
D ~ 1.5 km

✓ 2 horizontal tunnels ~100-200 m, excavated in chalk rocks
✓ highlight: both detectors to be located on the EDF power plant site
The Cruas site (Ardèche, France)

<table>
<thead>
<tr>
<th>Type</th>
<th>REP</th>
</tr>
</thead>
<tbody>
<tr>
<td>cores</td>
<td>4</td>
</tr>
<tr>
<td>Power</td>
<td>$11.7 , \text{GW}_{\text{th}}$</td>
</tr>
<tr>
<td>Coupling</td>
<td>1983-84</td>
</tr>
<tr>
<td>($%$, 2000)</td>
<td>79.0, 80.0, 68.9, 82.7</td>
</tr>
<tr>
<td>Constructor</td>
<td>Framatome</td>
</tr>
<tr>
<td>Opérateur</td>
<td>EDF</td>
</tr>
</tbody>
</table>

Near site: D~1 km, overburden >200 mwe
Far site: D~2 km, overburden >400 mwe

Cruas, 2×20 tons, D1=1 km, D2=1.8 km, 3 years $\Rightarrow \sin^2(2\theta_{13})<0.025$
The Cruas site (Ardèche, France)

Cruas, 2x20 tons, D1=1 km, D2=1.8 km, 3 years $\Rightarrow \sin^2(2\theta_{13})<0.025$
Cruas: Near detector @1 km !
& 4 fluctuating cores

\[ \Delta m^2 = 2.0 \times 10^{-3} \text{ eV}^2 \]

- Sensitivity slightly worst as \( D_{\text{near}} \) increase ...
- Worst sensitivity essentially due to the lost of statistical power (reactor-I only)
- See talk of G. Mention for a detail study of the reactor-detector setup
The Chooz site, Ardennes, France

... Double-$\text{CH}^{\theta_{13} \theta_{13}}Z$ ...
The Chooz site

- Near site: D~100-200 m [several options under study]
- Far site: D~1.1 km, overburden 300 mwe [former experimental hall]

- Positive signs from EDF for reusing the former CHOOZ site. Near site → civil engineering
- 2x11.5 tons, D1=100-200m, D2=1050m. Sensitivity: 3 years → $\sin^2(2\theta_{13}) < \sim 0.03$

<table>
<thead>
<tr>
<th>Type</th>
<th>PWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cores</td>
<td>2</td>
</tr>
<tr>
<td>Power</td>
<td>8.4 GWth</td>
</tr>
<tr>
<td>Couplage</td>
<td>1996/1997</td>
</tr>
<tr>
<td>(%) in to 2000</td>
<td>66, 57</td>
</tr>
<tr>
<td>Constructeur</td>
<td>Framatome</td>
</tr>
<tr>
<td>Opérateur</td>
<td>EDF</td>
</tr>
</tbody>
</table>
CHOOZ-Far: « marinière » gallery
CHOOZ-Far (CHOOZ-A)
CHO0Z-Far: « marinière » gallery
CHOÖZ-Far... ready to be used again!

Picture taken in September 2003
CHOOZ-Far
Improve CHOOZ is difficult! (Part I)

✓ Increase the luminosity \( L = \Delta t \times P(GW) \times V_{target} \)

- CHOOZ: 2700 events \( \Rightarrow \sigma_{stat} = 2.7\% \)

- Project Reactor/\( \theta_{13} \) with 40,000 evts \( \Rightarrow \sigma_{stat} 0.5\% \)
  @1.05 km, 50 kevts \( \geq 10 \) tons (scint. PXE) \( \times 8.4\ GW_{th} \times 3\ years \)

- Detector size \( \Rightarrow \) CHOOZ = 5 t
  \( \Rightarrow \) Could we increase the target mass @CHOOZ?

- Data taking time (3 ans \( \Rightarrow \) 5 ans) with high efficiency

- Choice of the scintillator:
  - Pure PXE + 0.1-0.2% Gd
  - CHOOZ scintillator
  - ~40% PC + 0.1% Gd+ 60% Min. oil
  BUT ONLY DRIVEN BY THE LONG TERM STABILITY PERFORMANCE !!!
Detector size scale

KamLAND
1000 t

Borexino
300 t

Reactor/$\theta_{13}$
Example $\sim 20$ t
(5 $\rightarrow$ 50 t)

Double CHOOZ
10 t!

@2.3 km: 30,000 evts $\gg$ 12 tons (scint. PXE) $\times$ 12 GWth $\times$ 5 years
CHOOZ-Near

Near detector @100-200 m from the nuclear cores in discussion with EDF
CHOOZ-Near
CHOOZ - Near new Laboratory

1 m
3.5 m
7 m
CHOOZ-Near new Laboratory

But underground water level @8 meter depth ...
CHOOZ—Near new Laboratory

High-Z material

~10-15 m
Status of the discussions with EDF

✓ **CHOOZ site has been secured.**
  - Strong support for the CHOOZ nuclear plant

✓ **Far site: 1.1 km & 300 mwe**
  - Existing laboratory
  - Available (7x7 m tank of CHOOZ-I)

✓ **Near site: 100-200 m**
  - Underground detector + man-made overburden
  - Feasibility confirmed by the power plant staff
  - Open question: how many mwe required? Precise answer needed ➔ cost issue ...
  - Civil engineering study financed by EDF!
# ν Flux @CHOOZ -Near & -Far

<table>
<thead>
<tr>
<th>10 t PXE (C$<em>6$H$</em>{18}$) 5.15 $10^{29}$ free H</th>
<th>100 m</th>
<th>200 m</th>
<th>1050 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν Flux s$^{-1}$, no osc.</td>
<td>0.0626 Hz</td>
<td>0.0156 Hz</td>
<td>0.000556 Hz</td>
</tr>
<tr>
<td>ν Flux d$^{-1}$, no osc.</td>
<td>5297</td>
<td>1324</td>
<td>48.0</td>
</tr>
<tr>
<td>ν Flux $y^{-1}$, no osc.</td>
<td>1.9333 $10^6$</td>
<td>483325</td>
<td>17536</td>
</tr>
<tr>
<td>ν Flux $y^{-1}$, sin$^2(\theta_{13})$=0.1</td>
<td>1.9324 $10^6$ (99.95%)</td>
<td>482727 (99.8%)</td>
<td>16830 (96.0%)</td>
</tr>
<tr>
<td>ν Flux, 3$y$, no osc.</td>
<td>5.80 $10^6$</td>
<td>1.449 $10^6$</td>
<td>52608</td>
</tr>
<tr>
<td>ν Flux, 5$y$, no osc.</td>
<td>9.66 $10^6$</td>
<td>2.417 $10^6$</td>
<td>87680</td>
</tr>
</tbody>
</table>
$\Delta m^2_{\text{atm}} = 2.0 \times 10^{-3} \text{ eV}^2$

Near Detector: ~ 1.8 $10^6$ events
- Reactor efficiency: 80%
- Detector efficiency: 80%
- Dead time: 50%

Far Detector: ~ 34 000 events
- Reactor efficiency: 80%
- Detector efficiency: 80%
Sensitivity to $\Delta m^2_{\text{atm}}$

$\Delta m^2_{\text{atm}} = 1.3 \times 10^{-3}$ eV$^2$
$\Delta m^2_{\text{atm}} = 2.0 \times 10^{-3}$ eV$^2$
$\Delta m^2_{\text{atm}} = 3.0 \times 10^{-3}$ eV$^2$

$\sin^2(2\theta_{13}) = 0.2$

Influence of $\Delta m^2_{\text{atm}}$
Improve CHOOZ is difficult! (Part II)

✓ Decrease systematic errors

• Systematic errors for CHOOZ: $\sigma_{\text{sys}} \sim 2.8\%$

• 1) Optimize the detector design for $\theta_{13}$ measurement

• 2) 2 identical detectors $\Rightarrow$ towards $\sigma_{\text{sys}} \sim O(0.1\%)$

• Strategy: gain a factor /10 to get $\sigma_{\text{rel}}[\text{detector1-detector2}] < 0.8\%$

• Backgrounds: $S/N > 100 \Rightarrow$ error < 1\%

$\Rightarrow$ See talk of H. de Kerret for detail study of Detector design and Backgrounds
Gd loaded scintillator

I) Pure PXE + 0.1-0.15% Gd
- New solution → Gd-ACAC Heidelberg, or Gd-Carbollylate
  → currently investigated @ MPIK
- Not compatible with acrylic
- Aromatic component C16H18 → low free H/cm³
  (~35% less than the CHOOZ scint.)

II) ~40% PXE/PC + 0.1% Gd + ~60 mineral oil :
- Coktail already used by Palo Verde, KamLAND, ... ?
  But problem of stability → LY ok, but d(Attenuation length)dt ~ 2 cm/day
- Aromatics + alkenes → more free H/cm³
  10 m³ PXE → ~10 t → 5.15 *10^29 free H
  10 m³ CHOOZ → 8.54 t → 6.87 *10^29 free H (33%)
- Compatible with acrylic

!!! LONG TERM STABILITY !!!
# Reactor induced systematics

<table>
<thead>
<tr>
<th>systematics</th>
<th>Error type</th>
<th>CHOOZ</th>
<th>Future Experiment</th>
<th>2 identical detector Low background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>Cross section</td>
<td>1.9%</td>
<td>-</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>Thermal power</td>
<td>0.7%</td>
<td>-</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>E/Fission</td>
<td>0.6%</td>
<td>-</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>Σ</td>
<td>2.1%</td>
<td>-</td>
<td>O(0.1%)</td>
</tr>
</tbody>
</table>
## Detector induced systematics

<table>
<thead>
<tr>
<th>Detector</th>
<th>Error type</th>
<th>CHOOZ</th>
<th>Future Experiment</th>
<th>Sim. Monte-Carlo</th>
<th>2 identical detector Low backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scint. Density</td>
<td>0.3%</td>
<td>0.3%</td>
<td></td>
<td></td>
<td>O(0.1%)</td>
</tr>
<tr>
<td>Target volume</td>
<td>0.3%</td>
<td>0.3%</td>
<td></td>
<td></td>
<td>O(0.1%)</td>
</tr>
<tr>
<td>% H</td>
<td>1.2%</td>
<td>1.2%</td>
<td></td>
<td></td>
<td>O(0.1%)</td>
</tr>
<tr>
<td>« Spill in/out » effect</td>
<td>1.0%</td>
<td>1.0%</td>
<td>X</td>
<td></td>
<td>O(0.1%)</td>
</tr>
<tr>
<td>Σ</td>
<td>2.5%</td>
<td>&lt;2.5%</td>
<td></td>
<td></td>
<td>O(0.1%)</td>
</tr>
</tbody>
</table>
A neutrino event

Anti-$\nu_e$ tag: $\bar{\nu}_e + p \rightarrow e^+ + n$, ~1.8 MeV Threshold

- Prompt $e^+$, $E_p=1-8$ MeV, visible energy
- Delayed neutron capture on Gd, $E_D=8$ MeV
- Prompt($\beta/\gamma$) - Delayed($\beta/\gamma$) $\Rightarrow$ pulse shape discrimination

Time correlation: $\tau \sim 30\mu$sec
Space correlation: < 1m$^3$

Anti-$\nu_e$ tag:

$\nu$ signal

No $\nu$ signal

spill in/out effect

Interaction $\nu$
Detector Designs (preliminary)

Based on the Chooz simulation (H. de Kerret, PCC)

Region I (1.4m & 1.4m)  ν Target  Gd loaded scintillator
Region II (0.35m & .35m)  γ Catcher  Scintillating buffer
Region III (1.0m & 1.0m)  PMT Buffer  non scintillating buffer
Region IV (0.6m & 1.0m)  Muon Veto  Water
Separation (15cm & <10cm?)  γ barrier  Steel
Region V (0m & ~1.0m)  n catcher  Water

• See talk of H. de Kerret for a detail detector design analysis
**Prompt e⁺ & Scintillating buffer**

- **Scintillating buffer:**
  - The positron energy is fully contained
  - \( E_{\text{threshold}} < E_{\text{min}}(e⁺) \rightarrow \text{No threshold effect} \rightarrow 0\% \text{ systematic!} \) (0.8 \% dans CHOOZ)
  - Relative calibration point between the two detectors
  - Background measurement at low energy (threshold foreseen ~500 keV)

But more accidental backgrounds due to PMT radioactives content \(^{40}\text{K}\)

\( \Rightarrow \) A third region (non scintillating) is needed to keep the acc. backgrounds low)
Gadolinium loaded scintillator (~0.1%)
- Gd $\rightarrow$ 8 MeV $\gamma$'s (capture on Gd : $86.6\%\pm1.0\%$ in CHOOZ, Eur.Phys.J. C27 (2003) 331-374)
- H $\rightarrow$ 2.2 MeV $\gamma$'s
- n capture prob. $\pm1.0\%$ (CHOOZ) $\rightarrow$ O% with 2 detectors (MC uncertainty)
- $\Delta t$ (e$^+\text{-}n$) $\rightarrow$ $\pm0.4\%$ (CHOOZ) $\rightarrow$ 0% with 2 detectors (MC uncertainty)

$n$ energy $\rightarrow$ $\pm0.4\%$ (CHOOZ) $\rightarrow$ Scintillating buffer mandatory (as in CHOOZ)

"spill in / spill out" effect $\rightarrow$ $\pm1.0\%$ (CHOOZ) $\rightarrow$ O(0.1%) 2 identical detectors needed !!!
### ν selection cuts systematics

<table>
<thead>
<tr>
<th>Coupures de sélection des ν</th>
<th>Error type</th>
<th>CHOOZ</th>
<th>Future Experiment</th>
<th>Sim. Monte-Carlo</th>
<th>2 detectors Low background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sélection cuts</td>
<td>Ee+ threshold</td>
<td>0.8%</td>
<td>0</td>
<td></td>
<td>0 (no cut !)</td>
</tr>
<tr>
<td></td>
<td>e+ position/géode (30cm)</td>
<td>0.1%</td>
<td>&lt;0.1%</td>
<td></td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>n capture</td>
<td>1.0%</td>
<td>&lt;1.0%</td>
<td>X</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>En</td>
<td>0.4%</td>
<td>&lt;0.4%</td>
<td></td>
<td>O(0.1%) - calibration</td>
</tr>
<tr>
<td></td>
<td>n pos./géode (30 cm)</td>
<td>0.1%</td>
<td>&lt;0.1%</td>
<td></td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>Distance (e+-n)</td>
<td>0.3%</td>
<td>0</td>
<td></td>
<td>0 (no cut ?)</td>
</tr>
<tr>
<td></td>
<td>Δt (e+-n)</td>
<td>0.4%</td>
<td>&lt;0.4%</td>
<td>X</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>n multiplicité</td>
<td>0.5%</td>
<td>O(0.1%)</td>
<td></td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>Σ</td>
<td>1.5%</td>
<td>&lt;1.1%</td>
<td></td>
<td>O(0.1%)</td>
</tr>
</tbody>
</table>

Sélection cuts:
- Ee+<8 Mev
- 6<En (MeV)<12
- de+-n < 100 cm
- 2<capture n<100μs
- n multiplicité =1 (ε_{tot}>70%)

## The experimental challenge

<table>
<thead>
<tr>
<th>Systematics</th>
<th>Error type</th>
<th>CHOOZ</th>
<th>Future</th>
<th>Sim. MC</th>
<th>2 identical detector</th>
<th>Low backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>Cross section</td>
<td>1.9%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>Thermal power</td>
<td>0.7%</td>
<td>0</td>
<td>O(0.1%)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E/Fission</td>
<td>0.6%</td>
<td>0</td>
<td>O(0.1%)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>∑</td>
<td>2.1%</td>
<td>0</td>
<td>O(0.1%)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Detector</td>
<td>Scint. Density</td>
<td>0.3%</td>
<td>0.3%</td>
<td>O(0.1%)</td>
<td>0</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>Target volume</td>
<td>0.3%</td>
<td>0.3%</td>
<td>O(0.1%)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>% H</td>
<td>1.2%</td>
<td>1.2%</td>
<td>O(0.1%)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>«Spill in/out» effect</td>
<td>1.0%</td>
<td>1.0%</td>
<td>X</td>
<td>O(0.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>∑</td>
<td>2.5%</td>
<td>&lt;2.5%</td>
<td>X</td>
<td>O(0.1%)</td>
<td></td>
</tr>
</tbody>
</table>

**Sélection cuts**

- Ee+<8 Mev
- 6<En (MeV)<12
- de+-n < 100 cm
- 2<capture n<100µs
- n multiplicité =1
  - (εtot>70%)

- Ee+ threshold
- n capture
- En
- Distance (e+-n)
- Δt (e+-n)
- n multiplicité

<table>
<thead>
<tr>
<th></th>
<th>CHOOZ</th>
<th>Future</th>
<th>Sim. MC</th>
<th>2 identical detector</th>
<th>Low backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.8%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>O(0.1%)</td>
</tr>
<tr>
<td></td>
<td>1.0%</td>
<td>&lt;1.0%</td>
<td>X</td>
<td>O(0.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.4%</td>
<td>±0.4%</td>
<td>O(0.1%)</td>
<td>O(0.1% - calibration)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.4%</td>
<td>&lt;0.4%</td>
<td>X</td>
<td>O(0.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5%</td>
<td>O(0.1%)</td>
<td>O(0.1%)</td>
<td>O(0.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5%</td>
<td>&lt;1.1%</td>
<td>O(0.1%)</td>
<td>O(0.1%)</td>
<td></td>
</tr>
</tbody>
</table>

Relative error between Near/Far detector < 0.8% seems possible [still under study]
Site depths

(Y. Declais)

Penly  
Chooz  
Cruas  

Kashiwasaki  
Diablo Canyon

Neutrino Flux, $\text{cm}^2\text{s}^{-1}$

$\mu$ vertical Intensity relative to surface

Depth, mwe (meters water equiv.)

(Y. Declais)
### Muon Flux @CHOOZ-Near

<table>
<thead>
<tr>
<th>Rock overburden, d=2.5 g.cm(^{-3})</th>
<th>15 m</th>
<th>20 m</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>m.w.e</td>
<td>37.5</td>
<td>50</td>
<td>62.5</td>
</tr>
<tr>
<td>Vertical (\mu) flux (m(^{-2}) s(^{-1}) str(^{-1}))</td>
<td>15.0</td>
<td>10.0</td>
<td>7.1</td>
</tr>
<tr>
<td>Total (\mu) flux (m(^{-2}) s(^{-1}))</td>
<td>31.4</td>
<td>20.1</td>
<td>10.9</td>
</tr>
<tr>
<td>Total (\mu) Flux / 24 m(^2)</td>
<td>~750</td>
<td>~500</td>
<td>~350</td>
</tr>
<tr>
<td>Attenuation</td>
<td>6.8</td>
<td>10.0</td>
<td>14.4</td>
</tr>
<tr>
<td>(&lt;E&gt;) GeV</td>
<td>9.0</td>
<td>12.2</td>
<td>14.4</td>
</tr>
<tr>
<td>Dead Time (450 (\mu)s/(\mu))</td>
<td>~34%</td>
<td>~23%</td>
<td>~16%</td>
</tr>
<tr>
<td>(&lt;E&gt;^{0.73} \times) Total (\mu) flux (m(^{-2}) s(^{-1}))</td>
<td>~189</td>
<td>~129</td>
<td>~103</td>
</tr>
</tbody>
</table>

### Muon Flux @CHOOZ-Far

<table>
<thead>
<tr>
<th>Rock overburden, d=2.5 g.cm(^{-3})</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>m.w.e</td>
<td>300</td>
</tr>
<tr>
<td>Vertical (\mu) flux (m(^{-2}) s(^{-1}) str(^{-1}))</td>
<td>0.3</td>
</tr>
<tr>
<td>Total (\mu) flux (m(^{-2}) s(^{-1}))</td>
<td>0.6</td>
</tr>
<tr>
<td>Total (\mu) Flux / 17 m(^2)</td>
<td>~10</td>
</tr>
<tr>
<td>Attenuation</td>
<td>326</td>
</tr>
<tr>
<td>(&lt;E&gt;) GeV</td>
<td>50.0</td>
</tr>
<tr>
<td>Dead Time (450 (\mu)s/(\mu))</td>
<td>~0.5%</td>
</tr>
<tr>
<td>(&lt;E&gt;^{0.73} \times) Total (\mu) flux (m(^{-2}) s(^{-1}))</td>
<td>~10</td>
</tr>
</tbody>
</table>
**ν_e detection & Backgrounds**

Anti-ν_e tag: \( ν_e + p \rightarrow e^+ + n \), \( \sim 1.8 \) MeV Threshold

- **Prompt e+,** \( E_p=1-8 \) MeV, visible energy
- **Delayed neutron capture on Gd,** \( E_D=8 \) MeV
- **Prompt(β/γ) - Delayed(β/γ) \( \rightarrow \) pulse shape discrimination

\[ \text{Time correlation: } \tau \sim 30\mu\text{sec} \]

\[ \text{Space correlation: } <1\text{m}^3 \]

**Several kinds of backgrounds**

- **Geophysical anti-ν_e's (negligible)**
- **Reactor anti-ν_e's (negligible)**
- **Background from radioactivity**
  - Rocks, detector material, water shielding, scintillator, & cosmogenics
- **Background induced by cosmic rays**
  - Radioactive nuclei produced in the detector
  - Neutrons induced by muons in detector & rocks

\[ \text{Depend on depth} \]

**Goal:** High signal to noise \( S/N \) and background known \( <\sim100\% \)
Preliminary Backgrounds Estimates

- **CHOOZ-I**: N/S ~ 4%

- **CHOOZ-II-Far (300 mwe)**: 11.5 tons → Signal × 2
  
  - Modification of the detector design → + expensive
  
  - **Uncorrelated**: CHOOZ-I backgrounds/10 → N/S ~ 0.1 / 50 < 1%

  - **Correlated events**: N/S < 1%
    
    CHOOZ-I: ~1 recoil proton per day
    
    CHOOZ-II: Liquid buffer 1m→2m → ~0.2 events per day

**CHOOZ-II-Near (50 mwe)**: Signal × 50-100 with respect to CHOOZ-Far

- **Key advantage**: D_{near} ~ 100m → Signal × 50-100 !

- **Uncorrelated**: CHOOZ-Far backgrounds × 50 → N/S < 1%

- **Correlated events**: CHOOZ-Far × 50 → N/S < 1%

(not comprehensive list of backgrounds ...)

→ See talk of H. de Kerret for detail study of Detector design and backgrounds
Muon induced production of radioactive isotope

- Background: Production of radioactive nuclei on $^{12}$C in the scintillator
- NA54: Isotope production on $^{12}$C target @SPS/CERN, $\mu$ beam @100/190 GeV $\rightarrow \sigma(E) \propto E^{0.73}$ (T. Hagner et. al.)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$</th>
<th>$E_{\text{max}}$ (MeV)</th>
<th>Rate (day$^{-1}$)</th>
<th>Ratio 300 / 20 mwe</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$B</td>
<td>0.02 s</td>
<td>13.4</td>
<td>-</td>
<td>-</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{11}$Be</td>
<td>13.80 s</td>
<td>11.5</td>
<td>$&lt; 2$</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{11}$Li</td>
<td>0.09 s</td>
<td>20.8</td>
<td>-</td>
<td>-</td>
<td>Correlated</td>
</tr>
<tr>
<td>$^{9}$Li + $^{8}$He</td>
<td>0.18 s</td>
<td>13.6</td>
<td>2$\pm$0.3</td>
<td>$\sim 0.1$</td>
<td>Correlated</td>
</tr>
<tr>
<td>$^{8}$Li</td>
<td>0.84 s</td>
<td>16.0</td>
<td>4$\pm$1</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{6}$He</td>
<td>0.81 s</td>
<td>3.5</td>
<td>14$\pm$1</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>20.38 m</td>
<td>0.96</td>
<td>770$\pm$49</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>19.30 s</td>
<td>1.9</td>
<td>98$\pm$12</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{9}$C</td>
<td>0.13 s</td>
<td>16.0</td>
<td>4$\pm$1</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{8}$B</td>
<td>0.77 s</td>
<td>13.7</td>
<td>6$\pm$1</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>$^{7}$Be</td>
<td>53.3 d</td>
<td>0.48</td>
<td>196$\pm$20</td>
<td>$\sim 0.1$</td>
<td>Uncorrelated</td>
</tr>
</tbody>
</table>

• Rates are given for the CHOOZ 10 t PXE case ($C_{16}H_{18}$)
• 5.15 $10^{29}$ free protons
• PXE scintillator : $d = 0.99 \rightarrow$ 10 tons detector
• PXE scintillator : $C_{16}H_{18} \rightarrow 4.58 \times 10^{29}^{12}C$
• Depth : 300 mwe
**Muon induced production of radioactive isotope**

- Background: Production of radioactive nuclei on $^{12}$C in the scintillator
- NA54: Isotope production on $^{12}$C target @SPS/CERN, $\mu$ beam @100/190 GeV $\rightarrow \sigma(E) \propto E^{0.73}$ (T. Hagner et. al.)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$ (s)</th>
<th>$E_{\text{max}}$ (MeV)</th>
<th>Rate (day$^{-1}$) 15 m (37.5 mwe)</th>
<th>Rate (day$^{-1}$) 20 m (50 mwe)</th>
<th>Rate (day$^{-1}$) 25 (62.5 mwe)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^-$</td>
<td>$^{12}$B</td>
<td>0.02</td>
<td>13.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$^{11}$Be</td>
<td>13.80</td>
<td>11.5</td>
<td>&lt; 30</td>
<td>&lt; 23</td>
<td>&lt; 18</td>
</tr>
<tr>
<td></td>
<td>$^{11}$Li</td>
<td>0.09</td>
<td>20.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$^{9}$Li + $^8$He</td>
<td>0.18</td>
<td>13.6</td>
<td>27±5</td>
<td>21±4</td>
<td>16±3</td>
</tr>
<tr>
<td></td>
<td>$^{8}$Li</td>
<td>0.84</td>
<td>16.0</td>
<td>51±18</td>
<td>39±14</td>
<td>31±11</td>
</tr>
<tr>
<td></td>
<td>$^6$He</td>
<td>0.81</td>
<td>3.5</td>
<td>201±20</td>
<td>155±16</td>
<td>124±12</td>
</tr>
<tr>
<td>$\beta^+$</td>
<td>$^{11}$C</td>
<td>20.38 m</td>
<td>0.96</td>
<td>11369±729</td>
<td>8765±562</td>
<td>6989±448</td>
</tr>
<tr>
<td></td>
<td>$^{10}$C</td>
<td>19.30 s</td>
<td>1.9</td>
<td>1450±183</td>
<td>1118±141</td>
<td>891±113</td>
</tr>
<tr>
<td></td>
<td>$^9$C</td>
<td>0.13 s</td>
<td>16.0</td>
<td>61±19</td>
<td>47±15</td>
<td>37±12</td>
</tr>
<tr>
<td></td>
<td>$^8$B</td>
<td>0.77 s</td>
<td>13.7</td>
<td>90±18</td>
<td>69±14</td>
<td>55±11</td>
</tr>
<tr>
<td></td>
<td>$^7$Be</td>
<td>53.3 d</td>
<td>0.48</td>
<td>2889±289</td>
<td>2228±223</td>
<td>1776±178</td>
</tr>
</tbody>
</table>

- Rates are given for the CHOOZ 10 t PXE case ($C_{16}H_{18}$)
- 5.15 $10^{29}$ free protons
- PXE scintillator: $d = 0.99 \rightarrow 10$ tons detector
- PXE scintillator: $C_{16}H_{18} \rightarrow 4.58$ $10^{29}$ $^{12}$C
- Depth: 2 hypotheses considered: 1) 37.5 mwe 2) 50 mwe 3) 62.5 mwe
Muon induced production of radioactive isotope

- Background: Production of radioactive nuclei on $^{12}$C in the scintillator
- NA54: Isotope production on $^{12}$C target @SPS/CERN, $\mu$ beam @100/190 GeV $\rightarrow$ $\sigma(E) \propto E^{0.73}$ (T. Hagner et. al.)

$^{11}$C
$^{7}$Be
$^{10}$C
$^{11}$Be + $^{8}$Li + $^{6}$He + $^{9}$C + $^{8}$B

events / day /10 tons PXE

$^{9}$Li + $^{8}$He
Muon induced production of radioactive isotope

- Background: Production of radioactive nuclei on $^{12}$C in the scintillator
- NA54: Isotope production on $^{12}$C target @SPS/CERN, $\mu$ beam @100/190 GeV $\rightarrow \sigma(E) \propto E^{0.73}$ (T. Hagner et. al.)

- Single Rate (uncorrelated)

  Dominated by $^{11}$C ($\beta^+$, 20.38 minutes half-life, end point @ 0.96 MeV)

  $\rightarrow$ Rate(CHOOZ-Near, 10t PXE) $\sim 9.10^3$/day @50 m.w.e $\rightarrow$ $\sim 3$ acc. events / day

  $\rightarrow$ Rate(CHOOZ-Far, 10t PXE) $\sim 800$/day @300 m.w.e $\rightarrow$ $\sim 0.03$ acc. events / day

  Single cosmogenics $\rightarrow [S/N]_{near} \sim 50/0.03>1500 \quad \& \quad [S/N]_{far} \sim 2500/3>750$

- Correlated events

  $\beta$-n cascade, $\tau$~few 100ms - Only $^8$He, $^9$Li, $^{11}$Li (instable isotopes)

  $\rightarrow$ Rate(CHOOZ-Near, 10t PXE) $\sim 30$/day @50 m.w.e

  $\rightarrow$ Rate(CHOOZ-Far, 10t PXE) $\sim 2$/day @300 m.w.e

  $\rightarrow$ Efficiency of those events after muon veto cut + analysis?

  But could be efficiently tagged:

  $\mu - n \rightarrow \beta - n$

  $< \quad ----- \quad >$

  200 $\mu$s

  $< \quad ---------------- \quad >$

  0.12-0.18 s

  $< \quad ----- \quad >$

  200 $\mu$s

  But impossible to tag without $\sim 100\%$ dead time $\rightarrow$ one must live with at the near site

  Correlated cosmogenics $\rightarrow [S/N]_{near} \sim 50/2>25 \quad \& \quad [S/N]_{far} \sim 2500/30> ~75$
Sensitivity to $\sin^2(2\theta_{13})$ after 1 year

$[\sin^2(2\theta_{13}), \Delta m^2_{\text{atm}}]$ correlation

$\Delta m^2_{\text{atm}}$

$\sin^2(2\theta_{13}) \@ 90\% \text{ C.L}$

#DNear 0.1 km
#NumberOfFreeProtonsNear 1.8944e+29 #RateNoOscNear 744129
#DFar 1.05 km
#NumberOfFreeProtonsFar 3.7888e+29 #RateNoOscFar 13498.9

#Global normalisation Fit is [ON ] with an error of 2%
#Relative normalisation Fit of Near/Far Detector is [ON ] with an error of 0.6%
#Shape Error Fit is [ON ] with an error of 2%
#ErrBin2BinNear is set to 1%
#ErrBin2BinFar is set to 1%
Sensitivity to $\sin^2(2\theta_{13})$

- $\sin^2(2\theta_{13}) \at90\% \ C.L$
  - 1 year $\Rightarrow \sin^2(2\theta_{13}) \times 0.045$
  
  - Flat background (T. Schwetz)
    - Near = 5% (100%)
    - Far = 1% (100%)

- 0.75 1.5 2.25 3.0 4
  
  - (pure PXE)
  - (PXE/PC + mineral oil)

- $@\Delta m^2_{\text{atm}} = 2.0 \times 10^{-3} \text{ eV}^2$

**Parameters:**

- #DNear = 0.1 km
- #NumberOfFreeProtonsNear = $1.8944 \times 10^{29}$ (11.5 tons PXE)
- #DFar = 1.05 km
- #NumberOfFreeProtonsFar = $3.7888 \times 10^{29}$ (11.5 tons PXE)

**Fits:**

- #Global normalisation Fit is [ON] with an error of 2%
- #Relative normalisation Fit of Near/Far Detector is [ON] with an error of 0.06%
- #Shape Error Fit is [ON] with an error of 2%

- $\sigma_{\text{bkg}}$: [near] = 1% [far] = 0.5%
- $\sigma_{\text{bkg}}$: [near] = 1% [far] = 1%
- $\sigma_{\text{bkg}}$: [near] = 2% [far] = 1%
Strong support for the EDF power company to do a 2nd experiment @CHOOZ! Reactor potential @CHOOZ: $\sin^2(2\theta_{13}) < \sim 0.03$, 90% C.L.
Current limit: CHOOZ : $\sin^2(2\theta_{13}) < 0.2 \Rightarrow$ discovery potential!

Technology / design well known (Chooz, Borexino, KamLAND, …)
$\Rightarrow$ few R&D needed: Gd loading (stability) + material compatibility
$\Rightarrow$ R&D in Saclay: material compatibility + mechanical constraints + scint. tests

Case under study: French $\nu$ target vessels & German scintillator (MPIK)

Experiment cost @CHOOZ:
2 x 11.5 tons, cost detectors <10 Meuros. (+ Civil engineering)

Our Goal @CHOOZ: Construction starts in 2005 (+ civil engineering)
Start data taking in 2007-2008!