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Towards Θ_{13} with Double Chooz

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Summary. — The Double Chooz experiment at the Chooz nuclear power station is designed to measure the last undetermined neutrino mixing angle Θ_{13} with a two-detector setup. This allows a significant reduction of the dominating systematic uncertainties compared to the CHOOZ experiment which currently still sets the limiting bound on Θ_{13}.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `07.05.Fb` – Design of experiments.

1. – Neutrino oscillations

There is now overwhelming evidence [1-4] for a non-diagonal mixing matrix in the neutrino sector, which gives rise to flavour changes of neutrinos and requires at least the addition of right-handed neutrinos to the standard model, observable as non-degenerate neutrino masses. For Dirac neutrinos, the relation of mass and flavour eigenstates can be written as a 3×3 matrix containing three mixing angles Θ_{ij} and one as yet undetermined CP violating Dirac phase δ:

$$(1)\quad \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}\mathrm{e}^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}\mathrm{e}^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

with $s_{ij} = \sin\Theta_{ij}$ and $c_{ij} = \cos\Theta_{ij}$, or for short

$$\vec{\nu}_{\text{flavour}} = \mathbf{U}\,\vec{\nu}_{\text{mass}},$$

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TABLE I. – *Global fits of neutrino properties* [6] *with* 1σ *bounds.*

Θ_{23}	$42.3^{+5.3}_{-2.8}$	Δm^2_{12}	$7.59 \pm 0.20 \cdot 10^{-5}\,\mathrm{eV}^2$
Θ_{13}	$6.8^{+2.6}_{-3.6}$	Δm^2_{31} (inverted)	$-2.40 \pm 0.11 \cdot 10^{-3}\,\mathrm{eV}^2$
Θ_{12}	34.4 ± 1.0	Δm^2_{31} (normal)	$2.51 \pm 0.12 \cdot 10^{-3}\,\mathrm{eV}^2$

U is known as the PMNS matrix. If neutrinos are Majorana particles, two additional phases α and β can occur:

$$\vec{\nu}_{\text{flavour}} = \mathbf{U} \begin{pmatrix} \mathrm{e}^{i\alpha/2} & 0 & 0 \\ 0 & \mathrm{e}^{i\beta/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \vec{\nu}_{\text{mass}}.$$

However, as Double Chooz is not sensitive to these phases, we will neglect them for the further discussion.

The neutrino masses enter as differences of squared masses into the description of the oscillation, conveniently written as

$$\Delta m^2_{ij} = m^2_i - m^2_j.$$

It is still undetermined if the ordering of the mass eigenstates from lightest to heaviest neutrino is

$$\begin{array}{rll} & m_{\nu_1} < m_{\nu_2} < m_{\nu_3} & \text{normal hierarchy,} \\ \text{or} & m_{\nu_3} < m_{\nu_1} < m_{\nu_2} & \text{inverted hierarchy.} \end{array}$$

Table I summarizes the state of our current knowledge about these basic neutrino properties. It is important to notice that for the 3σ bound, Θ_{13} fits are compatible with zero.

2. – Reactor neutrinos

The Double Chooz experiment uses beta-decay electron antineutrinos produced in the two $4\,\mathrm{GW}_{\mathrm{th}}$ reactor cores of the EDF Chooz B power plant at Chooz, France, to investigate the disappearance of these neutrinos over a base line of about 1 km due to non-vanishing Θ_{13}. The energy spectrum of these pure $\overline{\nu}_e$ reactor antineutrinos is determined by the beta-decay spectra of the fuel rod constituents and changes over time with the burn up, with average neutrino energies in MeV range below 10 MeV. To calculate the survival probability of an electron antineutrino of given energy, the general oscillation probability formula

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \mathrm{e}^{-\frac{i}{\hbar}(E_k - E_j)t}$$

can be written in ultrarelativistic approximation and with $c = \hbar = 1$

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\Theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4 \Theta_{13} \sin^2 2\Theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right). \quad (2)$$

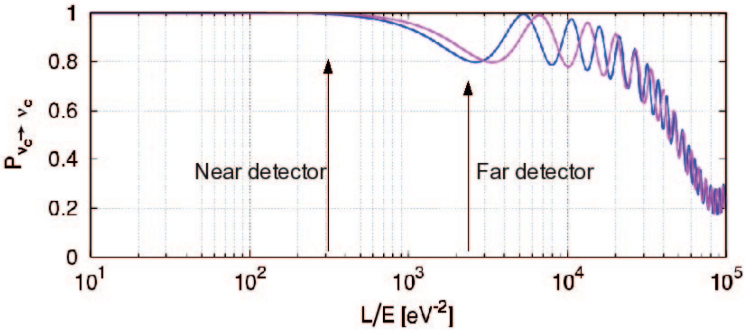

Fig. 1. – Survival probability of electron antineutrinos as a function of L/E for two different Δm_{31}^2 [7].

The resulting oscillation pattern is shown in fig. 1 as a function of L/E. Comparison of measured neutrino rate and spectral shape with calculations for different values of Θ_{13} can give direct evidence of $\overline{\nu}_e \to \overline{\nu}_x$ oscillations if the effect is large enough compared to systematic and statistic uncertainties. It should be noted that δ does not appear in the formula for the survival probability, eq. (2). Therefore, reactor neutrino experiments provide an unambiguous access to Θ_{13}, whereas beam experiments always suffer from degeneracies between δ and Θ_{13}. If Θ_{13} could be fixed by a reactor experiment, beam experiments could probe for CP violation in the leptonic sector by measuring δ.

3. – From CHOOZ to Double Chooz

The current bound on Θ_{13} is dominated by the results of the CHOOZ experiment [5], the predecessor of Double Chooz, which was located at the same power plant and used a 5 t Gd-doped liquid-scintillator target to identify neutrino-induced inverse beta decay

$$\overline{\nu}_e + p \to e^+ + n. \tag{3}$$

The signature of such an event is a delayed coincidence of the positron kinetic energy plus annihilation deposition followed by a gamma cascade released after n capture on Gd with $\tau \approx 30\,\mu$s. Due to kinematics, the neutrino energy can be directly inferred from the positron kinetic energy, which allows to reconstruct the energy spectrum of the detected neutrinos. The advantage of the Gd doped scintillator lies in the fact that Gd has a very high-n capture cross section and the energy released in gammas after capture is between six and eight MeV, thus clearly above all singles background induced by radioactive sources in the detector materials. CHOOZ had a total runtime of 15 months, with about 7 months of background only data. Its final results were compatible with a no oscillation hypothesis at 90% confidence level.

To improve on the accuracy of CHOOZ, several steps can be taken. Statistics limitations can be tackled by longer runtime (CHOOZ was limited by scintillator degradation in this respect), larger target mass and a more powerful reactor complex. The main systematic uncertainties arise due to incomplete knowledge on reaction cross section, detection efficiency, reactor power, etc., which for CHOOZ resulted in an overall 2.7% relative error. This can be addressed by doing a *relative* measurement with two identical

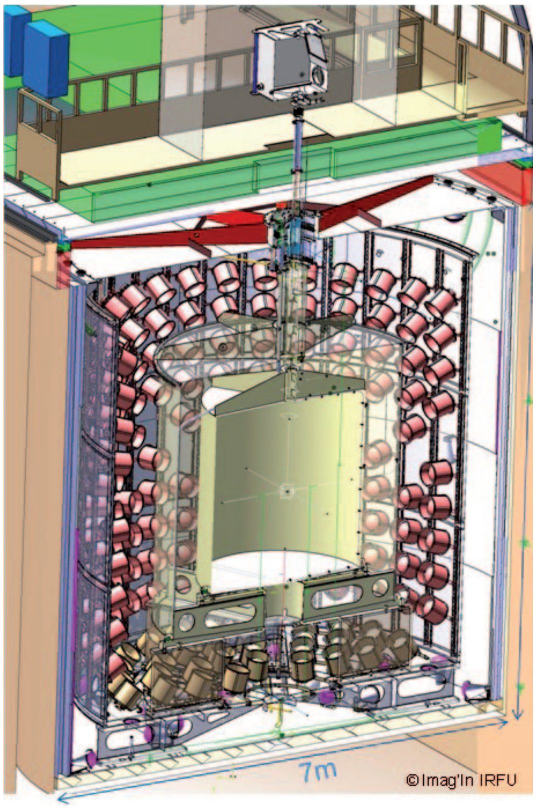

Fig. 2. – The Double Chooz detector design.

detectors—one close to the neutrino source (the near detector), the other one (the far detector) close to the location of maximal oscillation effect (c.f. fig. 1). All reactor-based Θ_{13} experiments follow these well-known and published ideas [8].

For Double Chooz in particular, the chosen detector design (see fig. 2) increases the target mass to 8 t while still using the original CHOOZ lab with its 300 m.w.e. overburden for the far detector, whereas a new tunnel and lab is being constructed at a distance of about 400 m to the reactor cores for the near detector. Table II summarizes near and far detector location properties.

4. – The Double Chooz detectors

The Double Chooz detectors consist of four concentric liquid-filled cylindrical volumes, with a total diameter and height of about 7 m, built into a pit in the rock floor of the laboratories.

The innermost volume is the target, filled with $10\,\mathrm{m}^3$ of Gd-doped PXE-based scintillator. The scintillator is contained in an acrylics tank, into which different calibration sources can be introduced by means of a fish line or an articulated arm. In this way, a clearly defined fiducial volume exists, which allows a reduction on the number of analysis cuts.

TABLE II. – *Double Chooz near and far detector location properties.*

	Near	Far
Distance to reactor cores (m)	400	1050
overburden (m.w.e.)	115	300
Neutrino rate (1/d)	500	50
Muon rate in inner veto (Hz)	250	20

Surrounding the target is the gamma catcher, another acrylics vessel containing undoped PXE based scintillator with a light yield matched to that of the target scintillator. Its radius is 55 cm larger than the target, and fixed to it are guiding tubes through which calibration sources can be pulled. Its purpose is to make sure all gammas from n capture close to the target wall are fully contained within the scintillating volume.

The third volume is called the buffer volume. It is another 105 cm larger in radius compared to the gamma catcher, consists of stainless steel and is equipped with 390 10 inch Hamamatsu photomultipliers which are all tilted individually to face the detector center. It is filled with non-scintillating mineral oil, reducing the number of background events induced by impurities in the photocathode of the PMTs by separating them from the scintillating liquid itself. It also contains optical fibers and diffusors for LED and laser calibration.

The outermost volume is the inner veto, a 50 cm thick shell filled with LAB based scintillator and instrumented with 78 fully encapsulated 8 inch Hamamatsu PMTs with their own optical fiber plus LED calibration system. It will efficiently tag muons crossing the detector and allow for some monitoring of muon-induced fast neutrons that enter the detector from the surrounding rock.

A 17 cm thick steel shield surrounds the veto volume to suppress gammas from the rock.

Covering the whole top of the detector are four layers of plastic scintillator panels that constitute the outer veto. It will complement the muon detection efficiency of the inner veto, allow for greatly increased tracking capability and extend over the central chimney of the detector, closing this “hole” in the inner veto.

Substantial effort has gone into R&D to improve all aspects of the CHOOZ experiment. One main goal was to ensure target scintillator stability for the run time of the experiment, which is scheduled to be five years. The composition—developed by the Max Planck institute for nuclear physics in Heidelberg—has been shown by now to be stable over a period of 2.5 years, with no discernible degradation on the absorbance length of the liquid.

Other examples of Double Chooz R&D are the FADC modules used to digitize the PMT signals, which were developed in close collaboration of APC Paris and CAEN, or the dedicated muon simulation utilizing topological maps and geological information of the reactor site to faithfully recreate the muon spectrum at the detector locations [9].

5. – Backgrounds

Understanding background is absolutely mandatory for neutrino precision experiments aiming at below the percent level, due to the low event rate. For the delayed coincidence signature of the neutrino event, one can distinguish two types of background events:

- Accidental background: In this case, two independent processes randomly happen to deposit the right amount of energy with the right delay between them. Contributions to this background come from radioactive impurities in detector components or the surrounding rock, as well as from secondaries induced by muons. Background reduction can be achieved by strict selection of high-purity materials only, good shielding and an efficient muon veto. The Double Chooz Monte Carlo simulations, which have been cross checked against the background data measured by CHOOZ, indicate an expected rate of about 12 accidental background events for the near detector and two for the far detector per day.

- Correlated background: These events occur if one single process induces both a fake positron and neutron signal, effectively mimicking the neutrino signal. One way this can happen is when a fast neutron created in the rock by a muon that just missed the detector reaches the target, where it first loses energy to recoil protons, which can look like a positron signal, and then is captured on Gd. Muons crossing the detector can also create spallation products like ^{9}Li, which decay by beta and neutron emission. In principle, these crossing muons are all tagged by the muon veto, however the life time of these isotopes is of the order of 100 ms, which combined with muon rates of order of 100 Hz prohibits a hard vetoing of these events. To deal with this kind of background, one can either choose a deeper detector site, or trust to muon monitoring and detailed Monte Carlo modeling. Again, from the Double Chooz Geant 4 based Monte Carlo software, we expect about eight correlated background events for the near and two for the far detector per day.

6. – Status and time schedule

As of May 2010, the Double Chooz far detector closing and liquid filling is imminent. DAQ and data processing modules and supporting electronics are almost completely installed, and preparations for light tightness tests are ongoing. Fluid delivery and mixing is done in parallel, with the goal of gathering first detector data in late summer of this year.

The construction of the near detector laboratory is starting—the design is approved by EDF, it is fully funded and scheduled to be completed till the end of 2010, which would be followed by the near detector construction until the end of 2011 or the beginning of 2012.

7. – Systematics and sensitivity

Double Chooz will consist of two distinct phases—the first 1.5 years with far detector only data, and another 3.5 years of combined detector data. During the first phase, a systematic error of 2.7% is expected, as we do not profit from the two-detector setup. This will drop to 0.6% total systematic error once the near detector gathers data and many uncertainties cancel in the relative analysis (compare table III). Still, even with far detector only data, Double Chooz will reach a sensitivity limit of

$$\sin^2 2\Theta_{13} < 0.06$$

TABLE III. – *Double Chooz phases one and two systematics.*

Systematic errors	Absolute	Relative
Production cross section	1.9%	–
Reactor power	0.7%	–
Energy per fission	0.6%	–
Detector efficiency	1.5%	0.5%
Number of protons in target	0.8%	0.2%
Total	**2.7%**	**0.6%**

after 1.5 years, which will be improved by another factor of two to

$$\sin^2 2\Theta_{13} < 0.03$$

after a total runtime of five years, as is shown in fig. 3. In this way, the current limit on Θ_{13} can be improved by a factor of four.

8. – Conclusions

Double Chooz is one of several reactor antineutrino experiments currently under construction which aims at measuring the last undetermined neutrino mixing angle Θ_{13}. It utilizes improved detector design and a two-detector setup to reduce systematic uncertainties in order to lower the current limit on Θ_{13} by at least a factor of four to $\sin^2 2\Theta_{13} < 0.03$ during its five year run time. Determining Θ_{13} would allow beam experiments to probe CP violation on the leptonic sector in the form of the Dirac phase δ, which appears in the neutrino mixing matrix and is yet completely free. Double Chooz

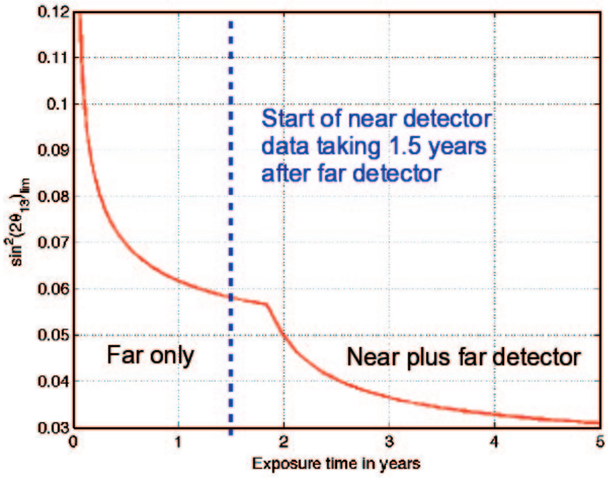

Fig. 3. – Sensitivity limit plot for Double Chooz at 90% CL.

will start data taking with the far detector during spring of 2011, and aims at starting its second, two detector phase at the end of 2011 or the beginning of 2012.

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