The Double Chooz Experiment: A Search for the Mixing Angle $\theta_{13}$

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Abstract. Double Chooz is an experiment to search for the electron neutrino component of the third neutrino mass eigenstate (i.e., a non-vanishing $\theta_{13}$ mixing angle) by measuring reactor antineutrino disappearance over a 1 km baseline. It will be the first of a new generation of neutrino experiments using identical detectors at different distances from the neutrino source to reduce the systematic errors due to the uncertainties on the neutrino flux and on the detector efficiency. The experiment is designed to measure the $\sin^2 2\theta_{13}$ quantity or improve the current best limit by almost an order of magnitude. Its potential is a measurement at 3$\sigma$ if $\sin^2 2\theta_{13} \geq 0.05$ or an exclusion down to 0.03 at 90% C.L. for $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV$^2$.

1. Introduction
The Double Chooz experiment [1] is currently under construction and consists of two liquid scintillator antineutrino detectors located at $\sim$400 m and $\sim$1 km from the reactor cores at the Chooz nuclear power station in the Ardennes region of northern France. This is the same site which hosted the previous most sensitive $\theta_{13}$ experiment at this baseline, CHOOZ [2]. The use of two detectors constructed to be as identical as possible is the primary distinguishing characteristic of Double Chooz. By comparing the electron antineutrino flux measured by the two detectors, Double Chooz will be remarkably sensitive to transformation of electron antineutrinos into other neutrino flavors: up to 5 times more sensitive than CHOOZ. The experiment is designed to detect oscillations whose amplitude is set by the last unknown mixing angle $\theta_{13}$. In the sections below, we first review the physics motivation and historical context of the Double Chooz experiment. We then describe the strategy used to increase the sensitivity to $\theta_{13}$ and present how the detectors have been designed to achieve our goal. We conclude with a discussion on the expected sensitivity of the experiment.

2. Physics motivation
Experiments with solar, atmospheric, reactor and accelerator neutrinos have provided compelling evidence for the existence of neutrino oscillations driven by non-zero neutrino masses and neutrino mixing [3]. Considering only the three known families, the neutrino mixing matrix is parametrized by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one CP violating phase $\delta$. The angle $\theta_{12}$ has been measured to be large, $\sin^2 2\theta_{12} \sim 0.8$, by the combination of the solar neutrino experiments [4] and KamLAND [5]. The angle $\theta_{23}$ has been measured to be close to maximum, $\sin^2 2\theta_{23} \sim 1$, by atmospheric neutrino experiments [6] as well as the long baseline accelerator neutrino experiments K2K [7] and MINOS [8]. However, we have only an upper limit on the
value of the mixing angle $\theta_{13}$, $\sin^2 2\theta_{13} < 0.14$ at 90% C.L. for $\Delta m_{31}^2 = 2.5 \times 10^{-3}$ eV$^2$, mainly given by the CHOOZ experiment. The CP violating phase $\delta$ is, at the present time, totally unknown. Genuine three flavor oscillation effects can only occur for a finite value of $\theta_{13}$. In addition, leptonic CP violation is also a three flavor effect scaled by $\sin^2 \theta_{13}$. Therefore, the measurement of the value of the last unknown mixing angle is not only of fundamental interest to understand leptonic mixing, but also necessary to plan for the future experimental campaign to measure $\delta$ which may help to answer the question of where the matter in the universe comes from, one of the greatest mysteries in fundamental physics today.

Reactor neutrino experiments measure the survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ of the $\bar{\nu}_e$ emitted by nuclear power stations at a given distance $L$. This probability does not depend on the CP violating phase $\delta$. Furthermore, thanks to the combination of the MeV range neutrino energies and the short baseline, the modification of the oscillation probability induced by the coherent forward scattering from matter electrons (the so-called matter effect [9]) can be neglected to first approximation. In the case of the Double Chooz experiment that is to say a baseline of $\sim 1$ km and a reactor antineutrino energy spectrum going up to 10 MeV, the $\bar{\nu}_e$ disappearance probability is well approximated by:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left( 1.27 \frac{\Delta m_{31}^2 L}{E} \right)$$

where $\Delta m_{31}^2 = m_3^2 - m_1^2$ is in eV$^2$, $L$ is the source to detector distance in m and $E$ is the $\bar{\nu}_e$ energy in MeV. This probability is free of parameter degeneracies and allows a “clean” measurement of $\theta_{13}$.

3. Historical context
As the Double Chooz experiment inherits from the first CHOOZ experiment with improvement towards the reduction of both systematic and statistical errors we will briefly summarize this experiment and its main result.

The CHOOZ experiment was located in the Ardennes region of France. It used the high $\bar{\nu}_e$ flux, about $10^{21}$ s$^{-1}$, emitted by the two PWR (Pressurized Water Reactor) nuclear reactors of 4.27 GW each to search for $\bar{\nu}_e$ disappearance 1050 m away. The detector was housed in an underground laboratory with an overburden of 300 m of water equivalent (mwe) providing, for the first time at a reactor, a strong reduction of the cosmic ray induced backgrounds. The detector was filled by a 5.6 m$^3$ Gd-doped liquid scintillator target, surrounded by a thick active (scintillating) buffer and muon veto. The external tank was surrounded by an additional layer of low radioactivity sand. The detector shielding was used to reduce backgrounds due to moderate neutrons produced by muons interactions outside of the detector as well as natural radioactivity gammas. Since the two Chooz reactors were commissioned after the start of the experiment, there was a unique opportunity to perform in-situ background measurements.

CHOOZ didn’t observe any evidence for neutrino oscillation. The result of the measurement is usually presented as the energy averaged ratio of the number of detected $\bar{\nu}_e$ events over the expected rate in the case of the null-oscillation hypothesis, $R = 1.01 \pm 2.8\% (\text{stat.}) \pm 2.7\% (\text{syst.})$. The CHOOZ experiment took data only during few months due to loss of transparency of the target liquid scintillator: the statistical error hence amounted for 2.8%. The systematic error amounted to 2.7% with contribution due to the lack of knowledge on the $\bar{\nu}_e$ source, on the number of target protons and on the detector efficiency (see table 1).

4. The Double Chooz strategy
The Double Chooz experiment involves 35 institutions over 9 countries with collaborators having already participated in reactor neutrinos experiments or in projects using liquid scintillator based
detection techniques. In order to improve the CHOOZ results one needs to reduce both statistical and systematic errors.

The reduction of the statistical error is made by an enlargement of the target volume up to 10.3 m$^3$. Moreover a new liquid scintillator has been developed with an improved stability of at least 5 years. The statistical error should therefore go down to $\sim 0.5\%$.

The reduction of the systematic error, dominated by the uncertainties on the $\bar{\nu}_e$ flux emitted by the reactors, is based on a relative measurement between two as identical as possible detectors. A far detector is located at the previous site of the CHOOZ experiment (1050 m away from the reactor cores) and a near detector is added in the vicinity of the cores at a mean distance of 400 m with an overburden of 120 mwe. The near detector ensures the flux normalization whereas the far detector looks for $\bar{\nu}_e$ disappearance. The same design is used for the inner part of both detectors at the near and far site to lower the detection efficiency error. The detectors will be filled with the same batch of liquid scintillator and the relative number of target protons will be known to better than 0.2% through a very precise weighing measurement. Furthermore the number of cuts needed at the analysis level is reduced thanks to a better detector design. The Double Chooz overall systematic error is expected to be 0.6% (see table 1).

|                | CHOOZ | Double Chooz |
|----------------|-------|--------------|
| Reactor $\bar{\nu}_e$ flux | 2.1%  | -            |
| Target protons number | 0.8%  | 0.2%         |
| Detector(s) efficiency | 1.5%  | 0.5%         |
| TOTAL           | 2.7%  | 0.6%         |

5. Detector design, signal and backgrounds

Like most reactor neutrino experiments, Double Chooz detects antineutrinos using the charged current interaction with free protons: $\bar{\nu}_e + p \rightarrow e^+ + n$. This produces a characteristic delayed coincidence signature of a “prompt” energy deposit, arising from $e^+$ energy loss and annihilation with an electron of the medium, followed by a “delayed” energy deposit, arising from gamma rays emitted by neutron capture on a nucleus. The prompt signal allows us to reconstruct the incident $\bar{\nu}_e$ energy. With a gadolinium concentration of 1 g/l in the target liquid scintillator, most of the neutron captures will occur on gadolinium, causing a delayed (typically 30 $\mu$s) energy deposit of approximately 8 MeV shared among several gamma rays.

The Double Chooz far detector is a cylinder of 7 m in diameter and height. It is made of concentric layers and is shown schematically in figure 1. In this design, a target of Gd loaded liquid scintillator is contained within an acrylic vessel where antineutrinos interact with free protons. A layer of unloaded liquid scintillator (the $\gamma$-catcher) surrounds the target to improve the neutron capture detection efficiency and to reduce systematic errors with neutron diffusion in and out of the target. A layer of non-scintillating mineral oil provides shielding against external radioactivity. Phototubes in the oil buffer detect light emitted by the scintillator. A 3-mm-thick stainless steel tank contains the buffer oil, provides either a support for the photomultiplier tubes or a barrier against light, gases, and liquids from outside the central detector.

The detector design includes a “veto” region filled with liquid scintillator surrounding the inner part of the detector. This region is optically and mechanically separated from the central detector and is contained within a 10 mm thick steel tank which isolates it from the exterior.
environment. Phototubes detect light from muons and high energy particle interactions in the veto scintillator.

The Double Chooz detector design includes a 150 mm thick layer of demagnetized, low radioactivity steel surrounding the inner veto, shielding the detector against radioactivity from the surrounding rock. The steel shield is composed of many long bars of steel, and covers the bottom, sides and top of the detector. This steel replaces the low activity sand used in CHOOZ, and allows the Double Chooz detector to be larger than the CHOOZ detector.

An outer veto muon detector is to be placed above and extended beyond the inner detector and steel shielding. It is made by plastic scintillator bars. This system will allow direct measurement of the efficiency of the inner veto and central detector for grazing muons and enable the study of muon-induced backgrounds from muons that miss the inner veto detector.

With a time window of 100 $\mu$s to select delayed coincidence, the backgrounds will be limited while maintaining a high efficiency for $\bar{\nu}_e$ events. Table 2 summarizes the expected antineutrino event rates and efficiency in the two detectors.

| Table 2. Antineutrino event rates and efficiencies. |
|---------------------------------------------------|
| Distance from the reactors (m)         | Near detector | Far detector |
| Detector efficiency                    | 80%           | 80%          |
| Dead-time efficiency                   | 90%           | 97%          |
| Reactor efficiency                     | 78%           | 78%          |
| Rate without efficiency ($d^{-1}$)     | 485           | 68.8         |
| Rate w. detector & dead-time efficiency ($d^{-1}$) | 348           | 53.4         |
| Integrated rate ($y^{-1}$)              | 99343         | 15200        |
Backgrounds for the experiment arise from many sources. Moderate neutrons and natural radioactivity gammas can produce a random coincidence of uncorrelated positron-like and neutron-like signals. Those events are called “accidental” backgrounds. The accidental background rate can be estimated quite accurately by measuring a fraction of the energy deposit which do not occur in temporal proximity to any other energy deposit. The second type of background is more dangerous and consists of a correlated positron-like and neutron-like signals which arise primarily from cosmic ray interactions. Cosmic rays outside the detector may produce one or more energetic neutrons, which may travel into the detector, deposit energy in a positron-like event by making protons recoil, and subsequently capture. Cosmic rays passing through the detector may produce relatively long lived $\beta$-n emitting isotopes, in particular $^8$He and $^9$Li, which latter emit an electron and a neutron in coincidence, closely mimicking the antineutrino signal. The inner veto and outer systems are all designed to address these correlated backgrounds. Table 3 summarizes the different expected background rates.

Table 3. Backgrounds.

|                               | Near detector | Far detector |
|-------------------------------|---------------|--------------|
| $\bar{\nu}_e$ rate (d$^{-1}$) | 485           | 69           |
| Accidentals (d$^{-1}$)        | 11            | 2            |
| Accidentals bkg/$\nu$ ratio   | 2.2%          | 2.9%         |
| Correlated (d$^{-1}$)         | 5.2           | 1.6          |
| Correlated bkg/$\nu$ ratio    | 1.1%          | 2%           |

6. Expected sensitivity

The Double Chooz experiment will consist of two different phases. The first phase (phase I) of the experiment will start in the fall 2010 and will take data with the far detector only. The second phase (phase II) will start during the year 2012, that is to say 1.5 years after the beginning of phase I, with both far and near detectors. The far detector integration is almost at the end and is currently in the filling stage while the civil work for the near detector will start in a few months.

Figure 2. The $\sin^2 2\theta_{13}$ sensitivity limit (90% C.L.) of Double Chooz assuming the value of $\theta_{13}$ is zero and the near detector is built 1.5 years after the far detector.
Figure 2 shows the $\sin^2 2\theta_{13}$ limit at 90% C.L. for $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$ assuming a value of $\theta_{13}$ equal to zero as a function of the time. The sensitivity drops quickly at the beginning of phase I and, with 10 times more statistics than the CHOOZ experiment, the best limit will be reached within 2 to 3 months. The sensitivity limit for the first phase will be $\sin^2 2\theta_{13} < 0.057$ if no oscillation is seen. For phase II, with a goal of having a total level of systematic uncertainties of 0.6%, the sensitivity reaches the level of $\sin^2 2\theta_{13} < 0.03$ if no oscillation is seen. The discovery potential is $\sin^2 2\theta_{13} \geq 0.05$ at 3$\sigma$ after 3 years with both detectors running.

7. Conclusion

Double Chooz will start data taking with the far detector this fall 2010 and will be the first new generation experiment to shed new light on the value of the last unknown mixing angle $\theta_{13}$.

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