Search for the $\theta_{13}$ mixing angle with the Double Chooz experiment

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Abstract. The Double Chooz reactor neutrino experiment will search for a non vanishing $\theta_{13}$ mixing angle with unprecedented sensitivity, which might open the way to unveiling CP violation in the leptonic sector. The measurement of this angle will be based in a precise comparison of the antineutrino spectrum at two identical detectors located at different distances from the Chooz nuclear reactor cores in France. Double Chooz is particularly attractive because of its capability to measure $\sin^2(2\theta_{13})$ to $3\sigma$ if $\sin^2(2\theta_{13}) > 0.05$ or to exclude $\sin^2(2\theta_{13})$ down to 0.03 at 90% C.L. for $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV$^2$ in three years of data taking with both detectors. The installation of the far detector at 1 km from the reactors is almost completed and the first neutrino interactions are expected by end 2010.

1. Introduction: The search for the $\theta_{13}$ mixing angle

During the last years, experiments with solar, atmospheric, reactor and beam neutrinos have provided clear evidence of the existence of neutrino oscillations driven by non-zero neutrino masses and neutrino mixing. The two mass differences which govern the oscillation probabilities have been measured with good precision and the $\theta_{12}$ and $\theta_{23}$ mixing angles are known to be large (almost maximal for $\theta_{23}$), dominating the solar and atmospheric oscillations respectively [1]. However, the $\theta_{13}$ angle (contributing to the effective decoupling between solar and atmospheric oscillations), the sign of $\Delta m^2_{31}$ (mass hierarchy) and the $\delta_{CP}$ violating phase are still unknown.

In particular, only an upper limit on the value of $\theta_{13}$ has been established indicating that the angle is very small compared to the other mixing angles. A three-flavor global analysis of the existing data provides a constraint on $\theta_{13}$ being $\sin^2(2\theta_{13}) < 0.12$ at 90% C.L [2]. This limit is essentially dominated by the result obtained by the CHOOZ reactor experiment [3] in France. This experiment measured the fraction of $\bar{\nu}_e$’s surviving at a distance of 1.05 km from the reactor cores to be $R = 1.01 \pm 2.8\%$ (stat) $\pm 2.7\%$ (syst). This result was mainly limited by the systematic uncertainties induced by the imperfect knowledge of the neutrino production and interaction.

The main goal of the present generation of neutrino oscillation experiments is the measurement of the last unknown mixing angle. This is of fundamental interest not only to understand the leptonic mixing but also because it determines the possibilities to observe CP violation in the leptonic sector with the forthcoming neutrino experiments.

1 On behalf of the Double Chooz collaboration
2. Reactor neutrinos

The information on the $\theta_{13}$ mixing angle can be essentially obtained from accelerator or nuclear reactor neutrino experiments. The long baseline accelerator experiments measure the appearance of $\nu_e$’s in a $\nu_\mu$ beam generated at long distance from the detector. The $\nu_\mu \rightarrow \nu_e$ transition depends on several oscillation parameters like the CP phase and the sign of $\Delta m^2_{31}$, in addition to $\theta_{13}$. Moreover, they can also be sensitive to matter effects due to the long baselines. Therefore, the measurement of $\theta_{13}$ will be affected by correlations and degeneracies between parameters and the sensitivity of the accelerator experiments to this parameter will be reduced.

On the other hand, reactor experiments are unique to provide an unambiguous determination of $\theta_{13}$. Nuclear reactors are very intense sources of $\bar{\nu}_e$’s coming from the $\beta$-decay of the neutron-rich fission fragments of fuel elements (238U, 235U, 239Pu and 241Pu). The mean energy released by fission is about 200 MeV and about 2 neutrinos above 1.8 MeV are emitted per fission. Thus, the expected neutrino flux is of the order of $10^{20}$ $\bar{\nu}_e$/s in 4$\pi$ for a typical 3 GWth reactor.

Reactor neutrino experiments will look for the disappearance of $\bar{\nu}_e$’s with energies extending up to 10 MeV over distances of the order of kilometers (short baselines) to maximize the disappearance probability. Due to the low energy range of the emitted electron antineutrinos, only disappearance measurements can be performed. The survival probability of $\bar{\nu}_e$’s emitted by a nuclear power station can be written as:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m^2_{31} L}{2E} \right) - \cos^2 \theta_{13}\sin^2(2\theta_{12}) \sin^2 \left( \frac{\Delta m^2_{21} L}{2E} \right)$$

$$+2\sin^2 \theta_{13} \cos^2 \theta_{13} \sin^2 \theta_{12} \left( \cos \left( \frac{\Delta m^2_{31} - \Delta m^2_{21}}{2E} \right) L \cos \frac{\Delta m^2_{31} L}{2E} \right)$$

where $E$ is the antineutrino energy and $L$ the distance from the source to the detector. Only the first term is relevant for short baselines. The oscillation amplitude is proportional to $\sin^2(2\theta_{13})$ and independent of the CP phase and the mass hierarchy. In addition, the combination of the MeV range neutrino energies and the short baseline implies that the modification of the oscillation probability induced by matter effects can be neglected to first approximation. Therefore, reactor neutrino experiments can perform a clean measurement of $\theta_{13}$, not affected by degeneracies or correlations between different oscillation parameters.

2.1. Neutrino signal and background in reactor experiments

Reactor antineutrinos are detected through the inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$. The signature of the neutrino interaction is the coincidence of a prompt signal from the positron energy loss and the resultant annihilation $\gamma$-rays and a delayed signal from the neutron capture on a nucleus. Many liquid scintillator $\bar{\nu}$ experiments use scintillator loaded with Gadolinium in their fiducial volume because of its large neutron capture cross section and high total $\gamma$ yield of 7-8 MeV. The time of coincidence in this case is reduced to 30 $\mu$s ($\sim$200 $\mu$s in the case of capture in H). The kinematics of the inverse beta decay reaction implies an energy threshold of 1.8 MeV. Above this limit the antineutrino energy is accurately reconstructed from the prompt signal.

The signature of a neutrino interaction can be mimicked by two kind of background events: accidentals and correlated. The accidental background corresponds to the coincidence of a positron-like signal coming from natural radioactivity of the surrounding environment or of the detector materials, with a neutron induced by cosmic muon spallation in the surrounding rock and captured in the detector. 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 are correlated events that mimic both parts of the coincidence signal. The positron-like and neutron-like signals come either from fast neutrons induced by cosmic muons, which can produce proton-recoils in the target scintillator
and subsequently are captured after thermalisation, or from the $\beta$ - n decay of long-lived (∼100 ms) cosmogenic radioisotopes ($^6$Li, $^8$He) produced by cosmic muons passing through the detector.

3. The Double Chooz experiment

Some of the largest systematic uncertainties of the CHOOZ reactor experiment were related to the accuracy to which the original neutrino flux and spectrum were known. In order to improve the CHOOZ sensitivity to the $\theta_{13}$ mixing angle, a relative comparison between two or more identical detectors located at different distances from the power plant is required. The first one, located at few hundred meters from the nuclear cores, monitors the neutrino flux and spectrum shape before neutrinos oscillate. The second detector, located 1-2 km away from the cores, searches for a departure from the global solid angle effect of the neutrino energy spectrum. At the same time, the statistical error can also be reduced by increasing the exposure and the fiducial volume of the detector. Moreover, backgrounds can be further reduced with a better detector design, using veto detectors and external shields against muons and external radioactivity.

Based on the previous strategy, the Double Chooz experiment [4] will try to improve our knowledge on the $\theta_{13}$ mixing angle within a competitive time scale and for a modest cost. The Double Chooz collaboration involves institutes from Brazil, France, Germany, Japan, Russia, Spain, UK and USA.

The experiment is being installed in the Chooz-B nuclear power plant in the Northeast of France. The maximum operating thermal power of the two cores is 8.54 GW$_{th}$. The far detector is located at 1050 m distance from the cores in the same underground laboratory used by the CHOOZ experiment, saving cost and time. It provides a quickly-prepared and well-shielded (300 m.w.e.) site with near-maximal oscillation effect and valuable knowledge about backgrounds from CHOOZ. A second identical detector (near detector) will be installed at 400 m away from the reactor cores to cancel the lack of knowledge of the neutrino spectrum and reduce the systematic errors related to the detector. For the near site, a 85 m air ramp plus a 115 m tunnel will be excavated under a small natural hill (overburden 115 m.w.e.) and a near lab will be equipped.

3.1. The detector design

The CHOOZ detector design can be optimized in order to reduce backgrounds. The Double Chooz detectors (Fig. 1) consist of concentric cylinders and an outer plastic scintillator muon veto. The innermost volume (“target”) contains about 10 tons of Gd-loaded liquid scintillator (0.1% Gd) within a transparent acrylic vessel. This will be the volume for neutrino interactions. It is surrounded by a 55 cm thick layer of unloaded scintillator (“gamma-catcher”) contained in a second acrylic vessel. This scintillating volume is necessary to fully contain the energy deposition of gamma rays from the neutron capture on Gd as well as the positron annihilation gamma rays inside the central region. It also improves the rejection of the fast neutron background.

Surrounding the gamma-catcher, a 105 cm thick region contains non-scintillating oil inside a stainless steel “buffer” vessel. This volume allows to reduce by two orders of magnitude, with respect to CHOOZ, the level of accidental backgrounds coming mainly from the radioactivity of the photomultiplier tubes (PMTs). 390 low background 10” PMTs are installed on the inner wall and lids of the tank to collect the light from the central scintillating volumes, providing about 13% photocathode coverage.

The central detector is encapsulated within a “inner muon veto” tank, 50 cm thick, filled with scintillating organic liquid and instrumented with 78 8” PMTs. It allows the identification of muons passing near the active detector that can create spallation neutrons and backgrounds coming from outside. Because of space constraint, the 70 cm sand shielding of CHOOZ is
replaced by a 15 cm iron layer to protect the detector from rock radioactivity and to increase the target volume. An “outer muon veto” made of plastic scintillator strips covers the top of the main system and provides additional rejection power for cosmic-induced events. It can be used for constant mutual efficiency monitoring with the inner veto.

Calibration systems will be deployed periodically into the detector allowing to check the stability of the system and measure the detection efficiency and the detector energy response for positrons, gammas and neutrons. The deployment of radioactive sources must be performed in a clean environment under a dry nitrogen atmosphere. A glove box interface with an associated clean room will be installed on the top of the detector.

3.2. Improvements with respect to CHOOZ

The CHOOZ experiment took data only during few months due to loss of transparency of the target liquid scintillator, arriving to a statistical error of 2.8%. Double Chooz expects to reduce this error by the enlargement of the target volume up to 10.3 m$^3$. Moreover, a new high-quality liquid scintillator has been developed with an improved stability of at least five years. The statistical error should therefore go down to $\sim 0.5\%$ after three years of data taking.

Many systematic uncertainties that affected CHOOZ and all previous single-baseline reactor neutrino experiments are greatly reduced by having both near and far detectors. Table 1 summarizes the systematic uncertainties in the measurement of the antineutrino flux comparing both CHOOZ and Double Chooz detectors.

Though an uncertainty from the neutrino contribution of spent fuel pools remains, it is negligible for Double Chooz. The neutrino rates are proportional to the number of free protons inside the target volumes, which will be experimentally determined by a weighing procedure at the filling with a precision of 0.2%. Both detectors will be filled with the same batch of liquid scintillator. In addition, a comprehensive calibration system consisting of radioactive sources deployed in different detector regions, laser light flashes and LED pulses, will be enforced to correct the unavoidable differences between the two detector responses. The optimization of the Double Chooz detector design allows to simplify the analysis and to reduce the detection
Table 1. Systematic uncertainties in CHOOZ and Double Chooz reactor experiments.

|                  | CHOOZ  | Double Chooz |
|------------------|--------|--------------|
| Reactor fuel cross section | 1.9%   | –            |
| Reactor power    | 0.7%   | –            |
| Energy per fission| 0.6%   | –            |
| Number of protons | 0.8%   | 0.2%         |
| Detection efficiency | 1.5%   | 0.5%         |
| **TOTAL**        | 2.7%   | 0.6%         |

efficiency systematic errors up to 0.5% while keeping high statistics. Therefore, the dominant detector related systematic error is expected to be kept below 0.6%.

The selection of high pure materials for detector construction and passive shielding around the active region provide an efficient protection against accidental background events. The inner and outer veto systems and the inner detector muon electronics are designed to address the correlated background. The total background rate is estimated to be 3-4 events per day in the far detector to be compared with a neutrino rate of $\sim 50$ per day. The error originated by the background subtraction in both detectors is expected to be less than 1%.

3.3. Expected sensitivity

The Double Chooz experiment will consist of two different phases. In a first phase, the far detector will start taking data alone. In a few months the previous CHOOZ limit will be surpassed. After $\sim 1.5$ years of data taking with one detector, Double Chooz will be sensitive to $\sin^2(2\theta_{13}) > 0.06$ (Fig. 2), a factor 3 better than CHOOZ.

![Double Chooz expected sensitivity limit](image)

**Figure 2.** Double Chooz expected sensitivity limit (90% C.L.) to $\sin^2(2\theta_{13})$ as a function of time for $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$, assuming that the near detector is built 1.5 years after the start of the far detector operation (end of 2010).

In a second phase, with both near and far detectors running simultaneously, the systematic errors can be reduced up to 0.6%. Double Chooz can measure $\sin^2(2\theta_{13})$ up to 0.05 at 3$\sigma$ or
exclude $\sin^2(2\theta_{13})$ down to 0.03 at 90% C.L. after three years of operation if no oscillation is seen.

3.4. Current status
The Double Chooz experiment is finishing the integration phase of the far detector in the existing underground laboratory at Chooz. The installation started in May 2008 with the integration of the external shield and followed by the assembly of the inner veto tank. Then, the buffer vessel was completed and the 390 $10^7$ PMTs successfully mounted in summer 2009. Finally, the acrylic gamma-catcher and target vessels were installed inside the buffer (Fig. 3) and the detector was closed. All the liquid scintillators have been produced and delivered, the DAQ and electronics systems are ready and the experiment is currently about to start the filling stage. First neutrino data are expected by end 2010.

![Figure 3. View of the acrylic vessels inside the buffer tank with the photomultipliers oriented towards the center of the detector.](image)

The tender process for the civil work of the near lab will start in October 2010 and the near site will be available by end 2011 to start with the near detector installation. The goal is to have both, near and far detectors, operative by mid 2012.

4. Conclusions
Double Chooz is a new generation reactor neutrino experiment using two identical detectors at different distances to measure the still unknown $\theta_{13}$ mixing angle. Double Chooz has almost completed the installation of the far detector and it is expected to start taking data at the end of 2010. The near detector will be ready by mid 2012 for the second phase of the Double Chooz experiment. After three years of operation with both detectors, Double Chooz will be able to measure $\sin^2(2\theta_{13})$ to $3\sigma$ if $\sin^2(2\theta_{13}) > 0.05$ or exclude the mixing angle down to $\sin^2(2\theta_{13}) > 0.03$ at 90% C.L. if no oscillation is observed.

References
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