Double-Chooz Neutrino Experiment

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Abstract. The Double Chooz experiment will use the electron anti-neutrinos produced by the Chooz nuclear power station to search for a non-vanishing value of the θ_{13} neutrino mixing angle. Double Chooz 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 to the detector acceptance. The far detector will be operative by the beginning of 2011. Installation of the near detector will occur in 2012.

1. Physics Motivation

Experiments with solar, atmospheric, reactor and beam neutrinos have provided compelling evidence for the existence of neutrino oscillations driven by non-zero neutrino masses and neutrino mixings [1]. The mixing in the leptonic sector can be parametrized in terms of 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) and the CP violating phase δ_{CP}. θ_{12} and θ_{23} have been measured to be large (almost maximal) while the value of the third mixing angle, θ_{13}, is not known, and is constrained to be small compared to the other two angles. δ_{CP} is totally unknown. The three-flavor neutrino oscillation framework also includes two mass-squared differences: Δm^2_{21} and Δm^2_{31}.

The best limit of θ_{13} was established by the CHOOZ experiment [2] from the non-observation of disappearance of reactor electron anti-neutrino at the scale of Δm^2_{32}. However, the current bound is obtained from a combination of global existing neutrino oscillation data [3], being $\sin^2 2\theta_{13} < 0.135$ at 90% C.L. The determination of θ_{13} is one of the primary goals in neutrino physics, in fact, genuine three flavor oscillation effects occur only for a finite value of θ_{13}. First, δ_{CP} becomes unphysical if θ_{13} is zero because it is also a three flavor effect. Hence, leptonic CP violation can only be tested by forthcoming experiments if θ_{13} is non-zero. In addition, any realistic possibility to determine the sign of Δm_{31} relies on a not-too-small θ_{13}. Finally, the determination of θ_{13} will provide important information on the mechanism of neutrino mass generation and the flavor structure in the leptonic sector [4].

Two different classes of experiments are able to measure small values of θ_{13}: accelerator neutrino beam experiments and nuclear reactor experiments. Accelerator experiments look for the appearance of ν_e in an almost pure ν_μ beam, due to oscillations. The appearance probability depends on all six oscillation parameters, being especially important the correlation of θ_{13} value with δ_{CP} and the sign of Δm_{31}, indeed, the correlation between δ_{CP} and θ_{13} can be only resolved if the accelerator operates also with anti-neutrinos.

Reactor neutrino experiments are able to provide a clean measurement of θ_{13} as they do not suffer from degeneracies and correlations between different oscillation parameters. However, reactor experiments are not sensitive to the value of δ_{CP}.

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2. Nuclear reactor experiments

The nuclear reactor experiments look for the disappearance of electron anti-neutrinos produced in reactor cores with an average energy of 2 MeV. Nuclear reactors are very intense sources of $\bar{\nu}_e$ coming from the β-decay of the fission products of fuel elements (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu). The survival probability is given by

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + O(\alpha^2)$$

with $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$. In order to measure θ_{13}, a distance to the detector of about 1 km is chosen to maximize the disappearance probability at the scale of Δm^2_{32}. This short baseline also prevents reactor experiment measurements to be affected by matter effects.

The $\bar{\nu}_e$ are detected via the inverse β-decay reaction: $\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$. The signature is a delayed coincidence between the prompt e$^+$ signal and the signal from the neutron capture. The neutron capture signal delay is about 200 μs in liquid scintillator and is reduced to about 30 μs in gadolinium loaded liquid scintillator. The positron energy is related to the $\bar{\nu}_e$ one by: $E_{\mathrm{e}^+} = E_{\bar{\nu}_e} - (M_\mathrm{n} - M_\mathrm{p})$ and the γ-ray energy released after the n-capture goes from 2 MeV (capture on H) to 8 MeV (capture on Gd). This characteristic signature is powerful enough to provide a $\bar{\nu}_e$ sample with a moderate level of background just applying a few selection cuts.

Nevertheless, the signal may be mimicked by background events which can be divided into two classes: accidental and correlated. The single events due to radioactivity from detector materials and surrounding rock is the responsible of the accidental background. The random coincidence between these events and a cosmogenic neutron would be drastically reduced by a careful selection of the materials used to build the detector. On the other hand, the two main contributions to the correlated background are: fast external neutrons and unstable isotopes, such as ^{9}Li and ^{8}He, with a β-neutron cascade. Fast neutrons may enter the detector and create recoil protons, faking the e$^+$ signal, and be captured after thermalization. Both types of events are coming from spallation processes of high energy muons. However, in the case of ^{9}Li and ^{8}He, the correlation with a muon signal is very difficult due to the relatively long-life of these isotopes (about 0.1 s).

3. Improving CHOOZ: The Double Chooz concept

CHOOZ experiment measured the electron anti-neutrino rate with a 2.8% statistical and a 2.7% systematic error [2]. The aim of upcoming experiments is to improve CHOOZ sensitivity by a factor 5 at least. This could be obtained by improving a factor five both statistics and systematics. To gain a factor 25 in the number of neutrinos with a detector twice bigger than CHOOZ, the detector must take data at least for 3 years. The stability of Gd doped liquid scintillator is the main limitation factor for long data taking. More difficult is the reduction of systematics. The dominant systematic error from the absolute measurement of the reactor neutrino flux (2%) and spectral shape will be removed by using an additional detector located a few hundred meters from the nuclear core to monitor the unoscillated neutrino flux. Figure 1 shows the neutrino oscillation probability at different reactor distances for a non-zero value of θ_{13}. In addition, if the detectors are identical, the uncertainty related to detector acceptance will be largely reduced.

The Double Chooz experiment [5] is located close to the twin reactor cores of the Chooz nuclear power station in the Ardennes (France). The far detector is placed at 1050 m distance from the cores in the same laboratory used by the CHOOZ experiment. It provides a quickly prepared and well-shielded (300 m.w.e.) site with near-maximal oscillation effect. The second identical detector (near detector) will be installed 410 m away from the nuclear cores under a hill of 115 m.w.e.

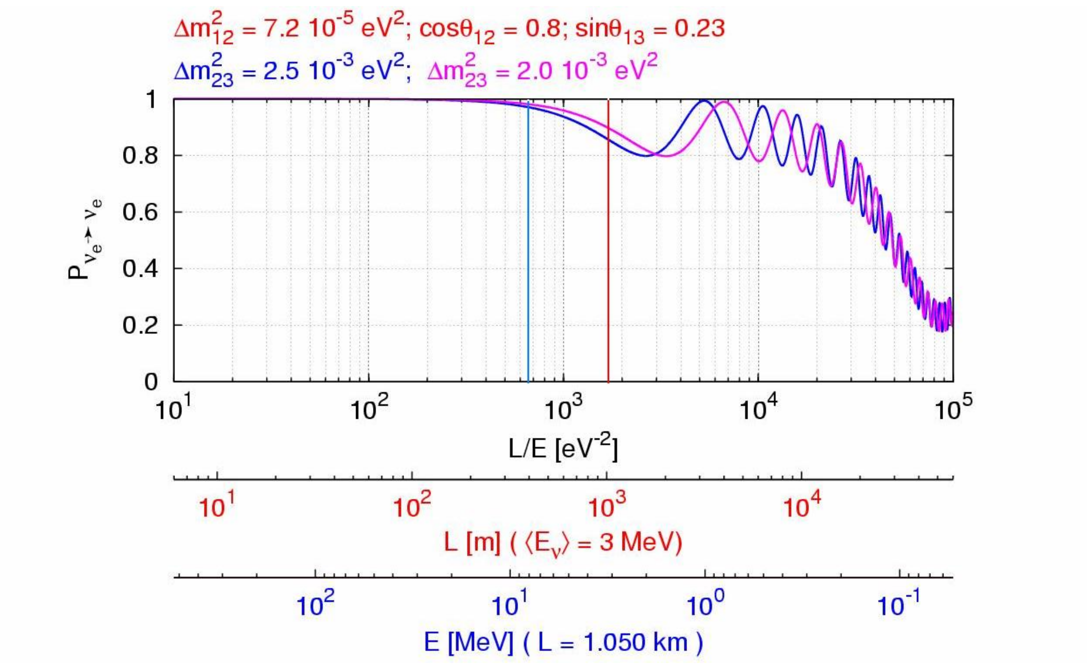

Figure 1. Neutrino oscillation probability as a function of L/E for $\sin\theta_{13} = 0.23$. The vertical blue line indicates the position foreseen for the near detector ($\sim$ 400m) while the red one shows the position of the far detector ($\sim$ 1km).

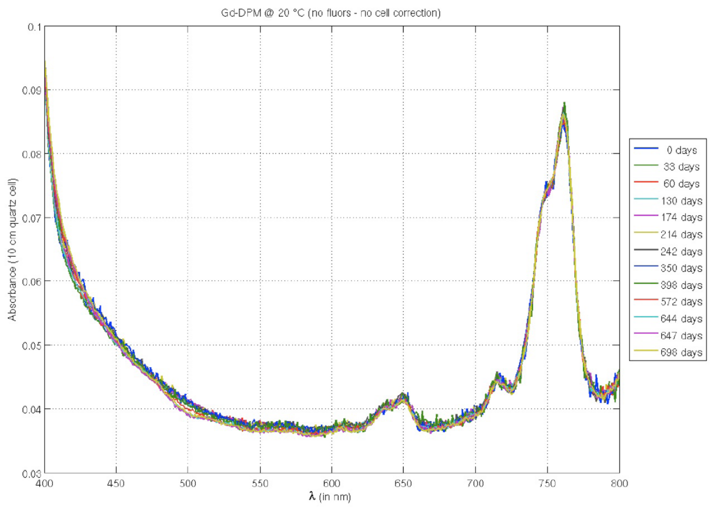

Figure 2. Optical properties stability of Double Chooz Gd loaded liquid scintillator. The absorbance for wavelength from 400 to 800 nm has been monitored for more than 2 years.

The detector has been designed to double the fiducial volume of the previous CHOOZ detector and the stability of a newly developed liquid scintillator has been successfully tested over 3 years, as it is shown in figure 2. The data taking period will extend to 3-5 years, in order to achieve 0.5% statistical error.

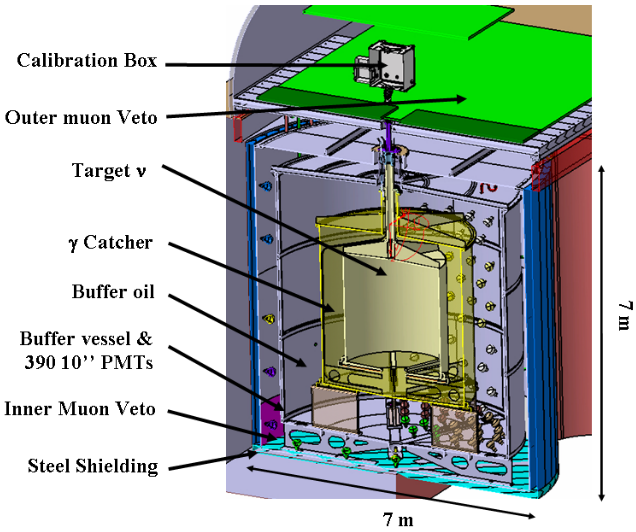

Figure 3. The Double Chooz detector

4. Double Chooz detector

The Double Chooz detectors (see figure 3) consist of concentric cylinders. The innermost volume is the neutrino target, a 10.3 m^3 acrylic cylinder, filled with 0.1% Gd loaded liquid scintillator. The target is surrounded by a 55 cm thick layer of unloaded scintillator (γ-catcher) contained in a second acrylic vessel. The function of this region is to get the full positron energy, as well as most of the neutron energy from the neutron capture on Gd. In addition, there is a 105 cm buffer of non scintillating oil to decrease the rate of single events from photomultiplier tubes (PMT) radioactivity. The buffer vessel (3 mm thick stainless steel cylinder) serves at the same time as support structure for PMTs. The detection system consists of 390 10 inches PMTs, providing about 13% photocathode coverage. The detector is encapsulated within an active cosmic-ray muon veto: a 50 cm thick region filled with liquid scintillator and instrumented with 78 8-inch PMTs. Outside this vessel, a 15 cm thick low activity steel shielding will protect the detector from the natural radioactivity of the rocks around the pit. Together with the buffer, it allows to reduce by two orders of magnitude the single event rate with respect to previous CHOOZ experiment. Finally, the upper part of the detector will be covered by plastic scintillator detector as an additional *outer muon veto*. The detector has been designed to minimize background, achieving in the far detector an expected background to signal ratio lower than 5%.

The detector is calibrated by a permanent non-intrusive tool of optical fibers that inject blue light to monitor the stability of liquids and PMT response. Other calibration systems will be deployed periodically into the detector allowing to measure the detection efficiency and the detector energy response for gammas and neutrons. The deployment of radioactive sources will be performed in a clean environment under a dry nitrogen atmosphere.

The far detector is in commissioning period, all PMT channels are operational, the read-out electronics is ready and the background rate is at the expected level.

5. Expected detector performance-sensitivity

In Double Chooz, the error due to the uncertainty on the anti-neutrino flux will be replaced by the relative normalization between detectors. The goal of the experiment is to reduce the systematic uncertainty to 0.6%. The expected systematic errors are shown in Table 1 together with the CHOOZ results. An effort is made for a precise measurement of the number of free

	CHOOZ	Double Chooz
Neutrino flux and reactor power	2.1%	-
Number of protons	0.8%	0.2%
H/C ratio and Gd concentration	1.2%	<0.2%
Detection efficiency	1.5%	0.5%

Table 1. Contributions to the overall systematic uncertainty on the absolute normalization factor in CHOOZ [2] and the expectations for Double Chooz.

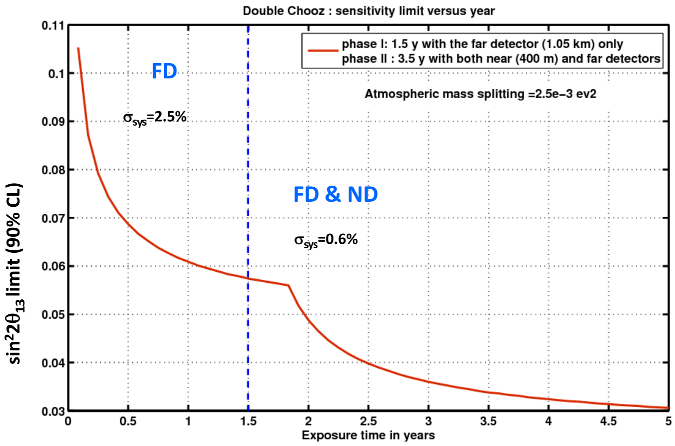

Figure 4. Double Chooz expected sensitivity limit (90% C.L.) to $\sin^2 2\theta_{13}$ as a function of time.

protons inside the target volumes, since the anti-neutrino rate is proportional to it. To do that, the target mass has been weighed with a precision of 0.2%. Since only one batch of liquid scintillator will be used to fill both detectors, the uncertainty in the molecular composition will be smaller than 0.2%. In addition, the optimization of the detector design allows to simplify the analysis and to reduce the detection efficiency systematic error up to 0.5%.

As we reported in the previous section, the signal to background ratio will be kept above 20 for the far detector and above 100 for the near one. The error originated by the background subtraction in both detectors is expected to be less than 1%.

The data taking of Double Chooz will be divided in two phases. During the first one (starting at the beginning of 2011) only the far detector will be present during 1.5 years. The expected systematic error is 2.5%, where the main contribution (about 2%) comes from reactor neutrino flux uncertainty. In this first period the sensitivity will be $\sin^2 2\theta_{13} < 0.055$ (at 90% C.L., for $\Delta m^2_{atm} = 2.5 \times 10^{-3}$ eV^2), a factor 2 better than current limit. The limit from CHOOZ will be reached in just a few weeks of operation, as it shown in figure 4. In the second phase both detectors will take data for 3 years. The full experiment will then achieve a final sensitivity of $\sin^2 2\theta_{13} < 0.03$ in the case of non-oscillation, assuming a relative normalization error of 0.6%.

6. Conclusions

The Double Chooz experiment is accomplishing the commissioning period of the far detector and will start the data taking in the following weeks. The near lab site will be available at the beginning of 2012 to accommodate the second detector. Both, near and far detectors, will be operational by mid 2012. After 3 years of operation of both detectors Double Chooz will be able to measure θ_{13} with 3σ effect if $\sin^2 2\theta_{13} > 0.05$. An intense R & D work has been carried out by the Double Chooz collaboration to validate the robustness of the double detector concept.

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