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# THE DOUBLE CHOOZ EXPERIMENT*

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The measurement of the last undetermined neutrino mixing angle $\theta_{13}$ is the main goal of the next generation of neutrino oscillation experiments. The present limit is dominated by the result of the Chooz experiment, which gives $\sin^2 2\,\theta_{13} \lesssim 0.10$–$0.15$ (depending on the true value of $\Delta m^2_{13}$), at 90 % confidence level. Double Chooz is a next generation reactor experiment aiming at exploring $\sim 80\,\%$ of the currently allowed parameter region, with a new detector at the Chooz site. The aimed sensitivity requires both the statistical and systematical errors to be significantly reduced with respect to past reactor experiments. In particular, the success of the project depends on the reduction of the systematics, made possible by the installation of a near identical detector and by the improvement of the detector design. The experimental concept and the status of Double Chooz are reviewed. Some of the accomplishments of the project R&D will be shortly discussed.

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## 1. Introduction

In the last decade our understanding of the fundamental properties of neutrinos has made formidable progress. A variety of experiments measuring solar, atmospheric, reactor and accelerator neutrinos have indisputably shown that neutrinos produced in a specific flavor *eigenstate* oscillate to other flavors. This is proof that neutrinos have mass and that they mix. Experiments with sensitivities spanning several orders of magnitudes in the oscillation parameter space have pinned down the values of two mass-squared differences and two mixing angles. For a review of the current status of the field, see Ref. [1].

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Two main issues still remain to be clarified: the absolute neutrino mass scale, and the third mixing angle $\theta_{13}$, which drives the amplitude of the still unobserved $\nu_x \to \nu_y$ oscillations (where $x$ or $y$ is $e$) at the frequency determined by $\Delta m^2_{13}$. At present $\theta_{13}$ is only known to be significantly smaller than the two other mixing angles $\theta_{12}$ and $\theta_{23}$. The negative result of the Chooz reactor experiment [2] has provided the most stringent upper-bound[1], $\sin^2 2\theta_{13} \lesssim 0.10$–$0.15$ at 90 % C.L. [2–4]. A less stringent bound has been given by the other $\sim 1$ km reactor experiment, Palo Verde [5]. The reported range for the Chooz limit corresponds approximately to the interval for the "atmospheric" mass splitting allowed by the combined results of SK, K2K and the first results of MINOS: $\Delta m^2_{13} = 2.0$–$3.0 \times 10^{-3}\,\mathrm{eV}^2$ (the bound on $\theta_{13}$ is anti-correlated with the true value of $\Delta m^2_{13}$).

The $\theta_{13}$ mixing angle — of fundamental theoretical interest *per se* — turns out to be the key parameter to access experimentally CP violation in the leptonic sector, which in turn could explain the matter/anti-matter asymmetry in the Universe. Several experiments aim at exploring in the near future with very different techniques and complementary approaches a large part of the region currently allowed by Chooz. Super-beam experiments will exploit the appearance channel $\nu_\mu \to \nu_e$ by using $\lesssim 1\,\mathrm{GeV}$ neutrinos and long baselines. The next generation reactor experiments aim at measuring the disappearance of $\overline{\nu}_e$ of a few MeV on a $\sim 1$–$2$ km baseline, with improved sensitivity with respect to Chooz. Double Chooz will be the first such experiment [6]. It will be installed nearby the CHOOZ-B nuclear power station operated by the French company Electricité de France (EDF) in partnership with the Belgian Electrabel and Societé Publique d'Electricité. The power plant is situated in the Ardennes region, northwest of France, very close to the Belgian border. It consists of two pressurized water reactors, both of the most recent N4 type, each providing $4.27\,\mathrm{GW_{th}}$.

Most theoretical models are unable to explain why $\theta_{13}$ should be much smaller than the two other mixing angles [1]. If the low value of $\theta_{13}$ is barely "accidental", its true value is most likely not very far from the present bound. A much smaller mixing would then be a strong hint for a new discrete flavor symmetry. In this context, the Double Chooz project offers a unique opportunity. By taking advantage of the existing Chooz facility, an improved, fast and small-scale experiment installed in the same site will be able to access a large part of the currently allowed parameter space, in an unrivalled time. Double Chooz will, therefore, be the first experiment to measure $\theta_{13}$, if no hidden symmetries forbid a sizable $\nu_3$ admixture in $\nu_e$. In case of a negative result, Double Chooz will provide the best constraint until the superbeam T2K experiment [7] will attain its designed sensitivity, around 2013.

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[1] The bound can be slightly improved by a global three-flavor analysis including the solar-$\nu$ and KamLAND results. See for example Refs. [3, 4].

## 2. The Double Chooz concept

The Chooz limit corresponds to the non-observation of $\overline{\nu}_e$ disappearance. This is expressed by the ratio $R$ between observed and expected reactor signal, averaged over the energy spectrum: $R = 1.01 \pm 2.8\,\%\,(\mathrm{stat}) \pm 2.7\,\%(\mathrm{syst})$ [2]. The potential of a new reactor experiment resides in the ability to reduce both the statistical and systematical errors with respect to Chooz. Taking into consideration the approved accelerator program, with the planned start-up of T2K at full beam intensity in 2011, the most natural first step of a reactor-based search is the construction of an experiment that requires minimal civil works. The Chooz site is ideal for this purpose, as the old Chooz laboratory is already available for the integration of a new detector. The overburden of about 300 mwe is adequate, as well as the oscillation baseline, with the detector being located at an average distance from the reactor cores of approximately 1.05 km.

It was early recognized that there is large room to reduce both statistical and systematical uncertainties with a clear-cut strategy [8]. Increasing statistics requires an optimal combination of large target mass, good efficiency and long run-time. As for the systematics, in Chooz they were dominated by the knowledge of the source, *i.e.* the $\overline{\nu}_e$ flux and spectrum ($\sim 2.0\,\%$). On the short term, very little can be done to reduce significantly this error, hence a new approach is proposed, which consists in shifting the reactor-based search of $\theta_{13}$ from an absolute to a relative measurement. All reactor-related uncertainties will be entirely or largely canceled by using a near detector, strictly identical to the far detector. Furthermore, with a two-detector concept some of the detector-related uncertainties are canceled as well, or significantly reduced. For example, this is the case for the number of target protons (known at $\sim 0.8\,\%$ in Chooz), since the same scintillator batch will be used (thus the H mass fraction will be the same in both detectors) and the same experimental procedure will be employed to measure the total target mass.

Whereas an underground site already exists to install the far detector, a new laboratory must be built for the near detector. Any distance between $\sim 100$ m and $\sim 400$ m would be suitable, however the necessary overburden to protect the detector from the cosmogenic backgrounds increases as the signal statistics decreases. The present baseline in the discussions with EDF considers the construction of a near laboratory at $\sim 280$ m from the cores, with an overburden of $\sim 80$ mwe (see later).

The error of the detection efficiency was the second most important systematics in Chooz ($\sim 1.5\,\%$). An identical near detector, already, cancels part of this error. The rest will be substantially reduced thanks to a new detector design, which includes a non-scintillating buffer between the PMTs and the $\gamma$-catcher and replaces the 75 cm low-radioactivity sand with a 17 cm steel shielding. The purpose is to lower the rate of singles, so that less off-line cuts — some difficult to calibrate — will be necessary.

In conclusion, Double Chooz aims at improving the sensitivity on $\theta_{13}$ by reducing both the statistical and systematical errors compared to the previous generation of reactor-based neutrino oscillation experiments. The former thanks to a larger target mass, and a longer running time. The systematics will be greatly reduced by using an identical near detector and an improved detector design. The ultimate sensitivity on $\theta_{13}$ will depend on the level of the residual systematics. The goal of Double Chooz is to achieve a total systematic error of 0.6 % relative between the two detectors, $\sim 0.5$ % from the detection efficiency and $\sim 0.2$ % from the relative normalization of the target mass. More details in [6].

## 3. Detector design

As in past reactor experiments, $\overline{\nu}_e$ are detected via the reaction:

$$\overline{\nu}_e + p \rightarrow e^+ + n \,, \tag{1}$$

with an energy threshold of 1.8 MeV. The neutron carries a very little energy, hence the positron energy deposition, boosted by the 1.024 MeV from its annihilation, measures $\overline{\nu}_e$ energy. An H-rich organic liquid scintillator is used as target and detection medium. The neutron issued from reaction (1) thermalizes in the scintillator and is then captured. The resulting gamma emission provides a powerful signature to reject background events.

In order to enhance the background rejection power of the $\overline{\nu}_e$ signature, Gd is dissolved in the scintillator, at a concentration of $\sim 1$ g/l. Captures on $^{155}$Gd and $^{157}$Gd, which have a huge cross sections for thermal neutrons, are followed by the emission of $\sim 8$ MeV in gammas, well beyond the background due to the natural radioactivity. A typical $\overline{\nu}_e$ event is then given by the coincidence of the prompt $e^+$ from Eq. (1) and a delayed $\sim 8$ MeV energy deposition, within a time window of $100\,\mu s$ (the characteristic n capture time for $\sim 1$ g/l Gd concentration is $\sim 30\,\mu s$).

The design of the Double Chooz detector is the result of an optimization process which has taken several requirements into consideration. Among the most important:

- Geometrical constraints imposed by the size of the existing pit where the first Chooz detector was installed. This is a cylinder of dimension 7 m, both in diameter and height.

- Maximization of the target mass given the above constraint.

- Efficient calorimetry of the reaction products, especially as regards the two 511 keV gammas issued from the $e^+$ annihilation.
- Accurate knowledge of the target volume and shape.
- Very efficient shielding of the inner sensitive volume against the radioactivity of the PMT system and surrounding rocks.
- Very efficient and possibly redundant tagging of cosmic-induced events.

The resulting design is shown in Fig. 1. From the center to the outside, the following sub-systems are found:

1. A central cylindrical acrylic vessel containing $\sim 8$ t of liquid scintillator doped with Gd at $\sim 1$ g/l. This is the target for the $\overline{\nu}_e$ interactions, the diameter is 230 cm, the height 245 cm.
2. A 55 cm thick volume concentric with the target and containing undoped scintillator. This region, called "$\gamma$-catcher", acts as a calorimeter; its purpose is to assure the full collection of the positron energy, and a good containment of the gamma cascade following $n$-capture on Gd.

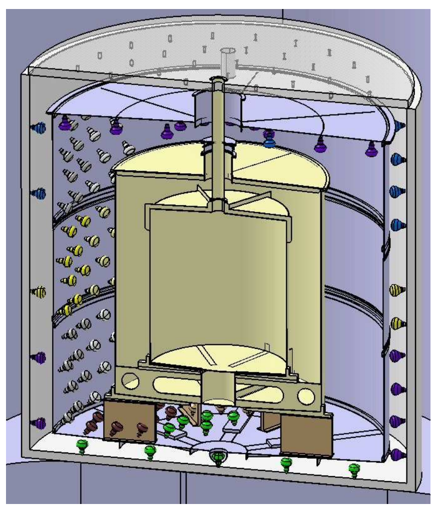

Fig. 1. Sketch of the Double Chooz detector. From the center outwards, the volumes are: target (8 t of Gd-doped scintillator), $\gamma$-catcher (17 t of undoped scintillator, 55 cm thickness), non-scintillating buffer (105 cm thickness, mineral oil), the PMTs (534 8″, low-background), inner veto (50 cm, mineral oil based scintillator), iron shielding (17 cm). The two inner vessels are made of transparent acrylic (8 mm and 12 mm), the buffer vessel is made of stainless steel and has 3 mm thickness. A chimney will allow the introduction of the filling tubes and calibration devices. The foreseen outer veto is not shown.

3. A 105 cm non-scintillating, highly transparent liquid buffer (mineral oil). This is one of the main improvements of the design with respect to the Chooz detector. The buffer aims at strongly attenuating the gammas emitted by the PMTs, and thus at reducing the rate of accidentals. 534 8″, low background PMTs are mounted on the buffer stainless steel tank. They are tilted towards the detector center and provide a $\sim 13.5\,\%$ photocathode coverage.

4. A 50 cm thick liquid scintillator veto equipped with $\sim 80$ PMTs. This region is called "inner veto", to distinguish it from the "outer veto" (see later). The inner veto can be made larger in the near detector, as the muon-induced background in the two detectors will be different, due to the different overburden.

5. A 17 cm steel shielding in the far detector, a $\sim 1$ m low-radioactivity sand layer in the near detector. A more compact shielding is used in the far detector to make room for a larger target and for the non-scintillating buffer, given the geometrical constraints imposed by the dimensions of the existing pit.

6. An outer veto covering a large surface on the top of the detector and, if necessary, a part of the sides. The design currently under study envisages 4 layers of tracker proportional gas tubes. This system provides redundancy with respect to the inner veto and, most importantly, tags and tracks "near-miss" muons.

## 4. Some achievements of the R&D

The ambitious goal of reducing both statistical and systematical error to $< 1\,\%$ requires both detectors to show stable and reliable performance for a time $> 1$ year, and to assure that the differences between the two detectors are limited, or controlled to a very high accuracy. In this section a non-exhaustive and subjective review is made of some of the major achievements accomplished by the Double Chooz collaboration, as regards the fulfillment of these requirements.

### *4.1. Gd-doped liquid scintillator*

Past reactor experiments have produced Gd-doped scintillators showing relatively fast degradations of their transparency. In Double Chooz the long-term stability of the target scintillator is of fundamental importance, either to assure a sufficiently long running time (several years), and to avoid systematics due to a possible different evolution of the liquids in the two detectors.

Gd-loaded scintillators are being produced since 2003 within the Double Chooz collaboration, as a natural follow-up of the expertise that the MPIK and LNGS/INR groups have acquired during the LENS project [9–11]. The scintillator base is chosen to be a PXE/dodecane mixture at a 20:80 volume ratio. The aromatic solvent (PXE) is diluted to reduce the risk of a chemical attack of the acrylic vessel. The admixture of a large fraction of dodecane, which has a higher H/C ratio compared to PXE, has also the advantage to increase the number of target protons. In spite of the great dilution, the mixture was measured to produce $\sim 78\,\%$ of the scintillation light of a pure PXE scintillator. As primary fluor PPO is used and few tens of mg/l of Bis-MSB (a wavelength shifter) are added, to shift the scintillator emission to a wavelength region of higher transparency. The resulting emission has a broad blue spectrum, peaked around 420 nm–450 nm.

Two families of chemical formulations have been developed to dissolve Gd in the organic scintillator base. One is based on carboxylic acids as ligand [10], the other on the chemistry of metal beta-diketonates [9, 12]. The chemical parameters controlling the long term stability of these systems are now well understood and both formulations have shown to be sound for Double Chooz. As an example, Fig. 2 shows the optical transmittance through 10 cm of one Gd-carboxylate and one Gd-beta-diketonate scintillator, monitored during >1 year. For both scintillators no significant degradation is

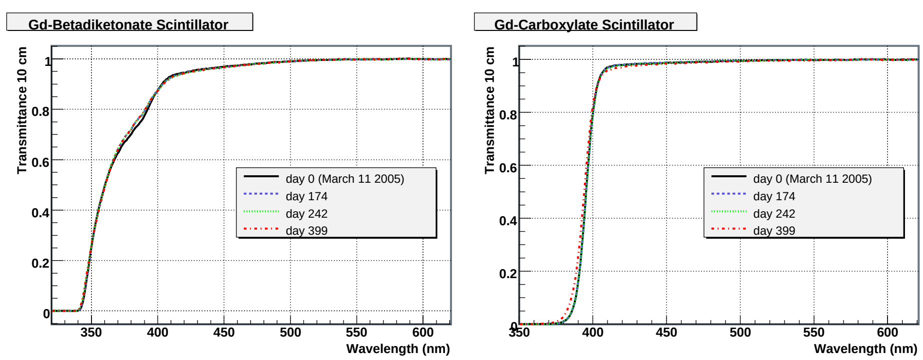


Fig. 2. Transmittance as a function of the wavelength for two R&D samples stored at room temperature. Left-hand side: Gd-Beta-diketonate (Gd-bdk) sample from MPIK-Heidelberg. Right-hand side: Gd-Carboxylate (Gd-cbx) from the LNGS/INR group at Gran Sasso. For both the common base is 20 % PXE + 80 % dodecane. The sharp cut-off at $\sim$ 400 nm for the Gd-cbx system is due to the fluors (the Gd-bdk sample shown here has no fluors dissolved). The higher "blue" absorbance of the Gd-bdk scintillator comes from optical impurities in the Gd-bdk material, which has not been purified prior to this test. Each curve corresponds to a scan at a different elapsed time with respect to the cell filling, from 0 to 399 days.

observed. Attenuation lengths in excess of $\sim 10\,\mathrm{m}$ at $430\,\mathrm{nm}$ are routinely obtained for the complete Gd-doped scintillators. Typical light yields are $\sim 60\,\%$ of that of the commercial, high-performing BC505.

As regards the $\gamma$-catcher, a very similar scintillator will be produced, however without Gd. The intrinsic light yield and transparency will be higher than in the target. The latter is advantageous, while an unbiased response of the detector requires the $\gamma$-catcher light yield to be accurately matched to the one of the target scintillator. This will be obtained by carefully tuning the fluor concentration.

### *4.2. Study of the mechanical and chemical stresses of the detector vessels*

The target and $\gamma$-catcher vessels will be made of cast acrylic. The thickness will be 8 mm and 12 mm, respectively. Acrylic offers many advantages: it is rigid, thus allowing the target volume and geometry to be precisely determined, very transparent to the scintillator emission, chemically robust against most solvents used in scintillators. Furthermore, the mechanical properties of acrylics are suitable for the construction of massive vessels, as was shown by SNO [13]. However, the safe operation of the Double Chooz vessels in a quite aggressive environment for several years has required a dedicated technological R&D. The highest risks are identified in the long term chemical compatibility with the scintillators, including the tightness of the gluing, and the effects of mechanical stresses, both permanent (during the normal detector running) and sporadic (during transportation, installation and filling).

First, the acrylic type has been selected upon an experimental campaign of compatibility and ageing tests, in which several acrylic samples have been exposed to the PXE/dodecane mixture, both with and without mechanical stress, both at room and elevated temperature. The best sample, a cast acrylic produced by the German manufacturer Röhm, has shown to resist to the scintillator even when subjected to levels of stress that are of one order of magnitude higher than the maximal values expected for the Double Chooz vessels. The latter stresses have been calculated by a mechanical "finite-element" simulation of the system. The same simulations have been employed to predict the stresses and deformations of the structure at dead load and as a function of the transport and filling procedures. As an example of the complexity of the problem, the simulations have shown that the transportation phase is hazardous for a completely assembled double acrylic vessel, due to the possibility of resonances with the vibrations generated by the suspensions of a truck. As a consequence, the vessels will be transported separately and glued on site with the collaboration of the acrylic manufacturer.

Similar simulations have been carried out for the buffer vessel. Here a crucial point was the definition of the minimal thickness allowed by mechanical constraints. For the physics it would be desirable to have the least dead, high $Z$ material mass, to reduce the possibility of muon-captures followed by neutron emission. The calculations for dead load (the most critical case) have shown that a 3 mm thickness is acceptable.

### *4.3. Mock-up*

As a part of the above validation research program, a 1/5-scaled[2] mechanical mock-up of the Double Chooz detector was built, a faithful replica from the target to the inner veto (Fig. 3 shows the double acrylic vessel). The mock-up has been filled in December 2005, the target volume with $\sim 110$ l of a Gd-doped scintillator with Gd concentration of 1 g/l; the $\gamma$-catcher with $\sim 200$ l of a density and light yield matched PXE/mineral oil/dodecane scintillator. Samples of the target and $\gamma$-catcher scintillator are monthly drained from the mock-up and analyzed. The analysis include the spectrophotometric measurement of the absorbance and the determination of the Gd content. The monitoring of these liquids and the final inspection of the vessels will assess the long term stability of the Double Chooz scintillators and acrylic under experimental conditions that are as close as possible to those of the real experiment. The preliminary results after a few months of running are encouraging.


Fig. 3. Double acrylic vessel of the Double Chooz 1/5 mock-up.

[2] The dimensions were scaled, but not the thicknesses of the vessels.

Validation procedures sharing the same methods are being developed to certify materials, other than the acrylic vessels, which are allowed to be in contact with the Gd-doped scintillator.

## 5. Sensitivity and discovery potential

Under the assumption that the total systematic error from the relative normalization of near and far detector is kept at 0.6 % and that the error originating from the subtraction of the backgrounds in both detector is $\sim 1\,\%$, Double Chooz will be able to exclude $\sin^2(2\theta_{13}) > 0.02$–$0.03$ at 90 % C.L. in 3 years of running with near and far detector, if no oscillation signal is seen. Conversely, for a true value of $\sin^2(2\theta_{13}) \gtrsim 0.04$ will be measured at $\geq 3\sigma$.

Since the far site is already available for the detector integration, while the near laboratory must be still constructed, it is foreseen that Double Chooz will first start taking data with the far detector alone, and that the start-up of the near detector will follow with a $\sim 1.5$ year delay. With no reduction of the systematical error with respect to Chooz, simply owing to the greater statistics and improved design, Double Chooz with the far detector only will reach a sensitivity of $\sin^2(2\theta_{13}) \sim 0.07$ (90 % C.L.) after one year of data-taking. These predictions are discussed in great detail in Ref. [6] and independently in Ref. [14].

## 6. Outlook

The Double Chooz collaboration is composed of several institutes from Europe (France, Germany, Spain, Russia, with the isolated participation of some Italian physicists) and the US. The project is approved and financed in France, and partly financed in Germany as well. The design of most detector parts is completed, or at a very advanced stage. The project is now mature for the start up of the construction of the far detector and of the civil works for the near laboratory in the forthcoming months. A close and solid collaboration with EDF has been established, both for the refurbishing and recommissioning of the far laboratory, and the construction of the near laboratory. In particular, as concerns the latter we meet regularly with EDF engineers and a preliminary study has been already carried out, which has identified the optimal location and design for the future laboratory. According to EDF, the excavation of $\sim 40$ m shaft at $\sim 250$–$300$ m from the reactor cores will be possible and sufficiently quick. Pending full financing, the far detector will be constructed during 2007 and will start up by the fall of 2007 or beginning of 2008. Parallel to this phase, the construction of the near laboratory will proceed. The site is expected to be available for detector integration by the fall of 2008. Double Chooz will then be operative with both detectors in 2009.

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