IL NUOVO CIMENTO Vol. 35 C, N. 1 Gennaio-Febbraio 2012
DOI 10.1393/ncc/i2012-11122-0

Colloquia: LaThuile11

Commissioning the Double Chooz detector

J. V. Dawson on behalf of the Double Chooz Collaboration
Laboratoire Astroparticule et Cosmologie - 10 rue Alice Domon et Léonie Duquet
75205 Paris, France

(ricevuto il 29 Settembre 2011; pubblicato online il 23 Gennaio 2012)

Summary. — The Double Chooz experiment is the first of the next wave of reactor experiments searching for a non-vanishing value of the mixing angle θ_{13}. The experimental concept and detector design are presented, and the most pertinent backgrounds are discussed. Operation of the far detector began in early 2011. Installation of the near detector will occur in 2012. Double Chooz has the capacity to measure $\sin^2(2\theta_{13})$ to 3σ if $\sin^2(2\theta_{13}) > 0.05$ or exclude $\sin^2(2\theta_{13})$ down to 0.03 at 90% for $\Delta m^2_{31} = 2.5 \times 10^{-3}\,\text{eV}^2$ with three years of data with both near and far detectors.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `29.40.Mc` – Scintillation detectors.

1. – Introduction

Neutrino oscillation has been clearly established via the study of solar, atmospheric, reactor and beam neutrinos. Combining these results requires the existence of (at least) three-neutrino mixing. In the current view, the PMNS mixing matrix relates the three neutrino mass eigenstates to the three neutrino flavour eigenstates parameterized by three mixing angles (θ_{12}, θ_{13} and θ_{23}) and one CP-violating phase δ_{cp} (for Dirac neutrinos). Neutrino oscillation experiments have made great progress in measuring the mixing angles and the two squared mass differences $\Delta m^2_{ij} = m^2_i - m^2_j$. However, one mixing angle θ_{13} remains unmeasured, and the mass hierarchy and the δ_{cp} phase are also still unknown. Upper limits to the value of θ_{13} have been made, indicating that this angle is very small with respect to the other two mixing angles. Whilst a measurement of θ_{13} would complete the knowledge of the mixing angles, even a more stringent upper limit would be useful since the size of θ_{13} has a great bearing on the possibility to observe CP violation in the leptonic sector with upcoming neutrino experiments (see, for example, [1] for a discussion of θ_{13} and CP violation discovery in forthcoming experiments).

The current value of θ_{13} is dominated by the bound given by the reactor experiment, CHOOZ [2], in which no oscillation was observed $R = 1.01 \pm 2.8\%(\text{stat.}) \pm 2.7\%(\text{sys.})$. Recent work on the calculation of neutrino fluxes from nuclear reactors [3] showed that previous calculations under-estimated the neutrino fluxes indicating a deficit in the number of observed anti-neutrinos for all reactor experiments at baselines shorter than 100 m (the Reactor Anti-Neutrino Anomaly). A re-evaluation of the CHOOZ result leads to a new exclusion limit, $\sin^2(2\theta_{13}) < 0.10$, at 90% CL for $\Delta m^2_{31} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$ [4].

The future direction of the field of neutrino oscillations is in some way governed by the size of θ_{13} such that even a more stringent upper limit would be of great use to the community. The size of θ_{13} essentially dictates whether current and future accelerator experiments can observe CP-violation in the leptonic sector, and also determine the neutrino mass hierarchy.

Reactor experiments provide a promising method to measure θ_{13}. These experiments search for the disappearance of electron anti-neutrinos emitted from the cores of the nuclear reactors. Equation (1) gives the survival probability of a $\bar{\nu_e}$ from a reactor, where E is the neutrino energy and L is the distance from the source to the detector.

$$\begin{aligned} P(\bar{\nu_e} \to \bar{\nu_e}) = 1 &- \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E} - \cos^4\theta_{13} \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m^2_{21} L}{4E} \\ &+ 2\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\theta_{12}\left(\cos\frac{(\Delta m^2_{31} - \Delta m^2_{21})L}{2E} - \cos\frac{\Delta m^2_{31} L}{2E}\right). \end{aligned} \tag{1}$$

For short baselines only the first two terms are relevant. With a well positioned detector (such that L/E is ~ 0.5 km/MeV), a detector might observe less neutrinos than anticipated indicating a non-zero value of θ_{13} and therefore these experiments are termed "disappearance" experiments. "Appearance" experiments, *i.e.* long baseline accelerator experiments, aim to measure the appearance of ν_es in a ν_μ beam.

Reactor based θ_{13} experiments have some advantages over long baseline accelerator experiments. They suffer less from parameter degeneracies, being independent on δ_{cp} and the sign of Δm_{31} and having only a weak dependence on Δm^2_{21}. Since the neutrino energies are low, ~ 1 to 10 MeV, and the detectors are positioned at short distances, there are no matter effects. The major drawback to this type of experiment is that there is limited knowledge on the neutrino production processes inside the reactors.

2. – Double Chooz

The Double Chooz experiment [5] is located at Chooz, the same site as the original CHOOZ experiment, in the Champagne-Ardennes region in France. The site contains two closely neighbouring nuclear reactors each with a thermal power of 4.27 GW. The Double Chooz concept is to use two identical detectors; one near, to effectively measure the neutrino spectrum and flux from the reactor, and one far, to observe any neutrino disappearance.

The far detector is located in the same underground laboratory as the original CHOOZ experiment (1 km from the two cores). This site is perfect for three reasons; a good L/E of 0.3 MeV/km, the cost is significantly reduced due to the existing laboratory, and the experimental background rate *i.e.* from muons, neutrons and rock radioactivity, etc. is already well measured with reactor-off data. The near detector underground laboratory is currently under construction at a distance of 400 m from the two reactors.

The target is a gadolinium loaded scintillator, with an interacting anti-neutrino of energy greater than 1.8 MeV causing an inverse beta decay of a proton:

$$\bar{\nu}_e + p \to n + e^+. \tag{2}$$

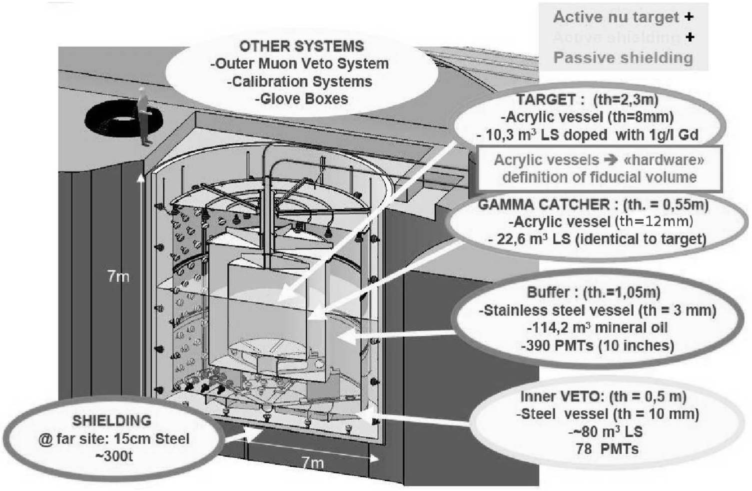

Fig. 1. – Design of the Double Chooz detectors.

The positron slows depositing its kinetic energy in the scintillator. It quickly annihilates; releasing two 511 keV gammas. The total prompt visible energy seen is some 1 to ~ 8 MeV and is directly related to the energy of the neutrino $E_\nu = E_{visible} + 0.8$ MeV. After a characteristic delay, the neutron slows and is captured; on gadolinium (absorption time of $30\,\mu$s) or on hydrogen. Gamma cascades from the captures give energy deposits of ~ 8 MeV (from gadolinium) and 2.2 MeV from hydrogen.

As the interaction cross-section rises (with the square of the energy) and the reactor neutrino spectrum falls in a similar fashion, the convolution of these two, the observed spectrum is roughly Gaussian in shape with a peak visible energy of ~ 3 MeV.

3. – Detector design

Figure 1 shows the detector and laboratory design. Both detectors are identical from the buffer tank (inner-most stainless steel vessel) inwards which is a physics requirement. Shielding against the radioactivity of the rock is provided by 15 cm of demagnetised steel for the far detector but less stringent shielding is required for the near detector.

Each detector is formed from a series of nested cylinders with each volume filled with different liquids; insensitive buffer oil for shielding, Gd-doped scintillator as the target and undoped scintillators for gamma rays, fast neutrons and muons.

The two inner vessels are acrylic and transparent to photons above 400 nm. The innermost vessel is the Target, with a diameter of 2.3 m, which contains 10 m^3 of gadolinium-doped scintillator; such that the scintillator contains 1 g/l of gadolinium. In this volume neutron-capture on gadolinium can occur releasing cascade gammas with an energy of ~ 8 MeV. More than 80% of neutron captures are on gadolinium rather than hydrogen. The definition of a neutrino candidate event is one in which neutron capture on gadolinium occurs.

Enclosing the target is the Gamma-Catcher volume, with a diameter of 3.4 m, which contains 22 m^3 of undoped scintillator. The purpose of this volume is to detect the gammas emitted in both the neutron-capture process and positron annihilation in the target, such that gammas emitted from neutrino events occurring in the outer volume of the target are detected. This results in a well-defined target volume.

Since the photomultipliers are the most radioactive component of the detector, the inner volumes are shielded by a buffer volume, with a diameter of 5.5 m, filled with non-scintillating paraffin oil. Events occurring in the acrylic volumes are detected by 390 10 inch low background photomultiplier tubes (Hamamatsu R7081 [6]) fixed to the inside of the stainless steel buffer tank. Uniquely the photomultiplier tubes are angled to improve the uniformity of light collection efficiency in the inner-most volumes.

The outer detector volume is steel walled, with a diameter of 6.6 m, and filled with scintillator. 78 8 inch photomultipliers (Hamamatsu R1408 [6]) line the outermost wall which is painted with a reflective white coating. This volume is the Inner Veto with the purpose of detecting and tracking muons and fast neutrons.

On top of the detector sits the Outer Veto. This comprises strips of plastic scintillator and wavelength-shifting fibres. The veto extends further than the detector diameter with the purpose of detecting and tracking muons. The precision of the entry point of a muon, X-Y position, will be far more precise than that achieved by the Inner Veto and detector. One of the main objectives is to tag near-miss muons, which interact in the surrounding rock (and not in the detector) but produce fast neutrons. Another important goal is to determine whether a muon entered the Inner Detector. Muons that do so can produce cosmogenic isotopes (*i.e.* via a photonuclear interaction on carbon), some of which will produce backgrounds for the experiment.

4. – Backgrounds

As each neutrino produces two time-correlated signals; that of the positron and a delayed capture of a neutron (with characteristic decay time of $30\,\mu$s), backgrounds can come from two sources; accidental and time-correlated.

The accidental component comes from the random chance that two events of appropriate energy interact within this characteristic time. Since these two events are unrelated this rate can easily be measured, based on the singles rate. The main source of events come from radioactive contamination with the dominant source being the photomultiplier tubes. For the accidental component to be well constrained, strict radioactive contamination limits have been placed on all parts.

The most difficult backgrounds to study are those that are, like our signal, time-correlated. From the experience of Chooz it is anticipated that Double Chooz will observe some ~ 1.5 events/day of false neutrino-like events. The Chooz experiment had a period of data-taking before operation of the nuclear reactors began and so the background could be very thoroughly investigated. The sources of the neutrino-like events observed were attributed to fast neutrons (muon-induced neutrons) and cosmogenically produced isotopes (also muon produced).

Fast neutrons can mimic neutrino signals by producing a proton-recoil (positron-like signal) and a delayed neutron capture. If the muon is seen by the experiment then these events can be tagged. More dangerous, however, are near-miss muons which interact in the rock releasing fast neutrons which interact in the detector. The primary purpose of the Outer Veto is to identify these events by covering an area wider than the detector itself.

Those cosmogenically produced isotopes that are dangerous for the experiment are those that result in electron emission followed by neutron emission, as these mimic well our neutrino signal. Two isotopes, ^{8}He and ^{9}Li, have long decay times (119 ms and

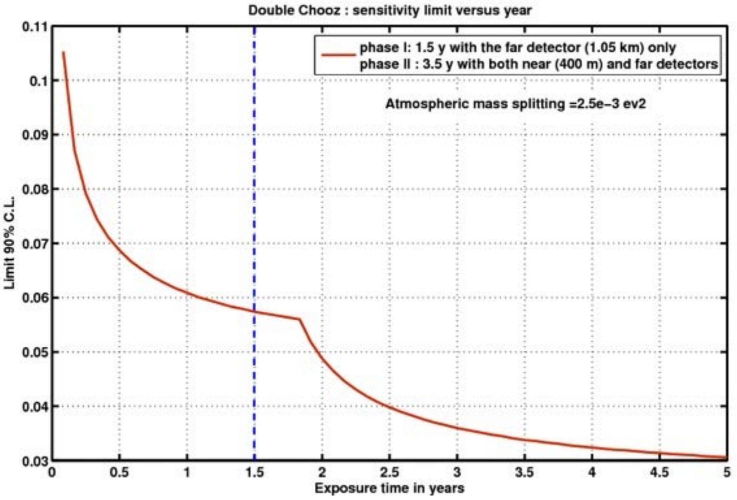

Fig. 2. – Sensitivity of the experiment, showing the first far detector only phase and the rapid improvement as the near detector is included.

174 ms, respectively) [7] rendering a hardware veto impractical. Coupling information from the Outer Veto (with precise muon entry points), Inner Veto and Inner Detector will allow reconstruction of muon tracks to identify muons that cross the Inner Detector.

5. – Improvements on Chooz

Improvements on the original Chooz experiment have been made in two ways; the detector design and the two-detector concept. The new detector target is more than twice as large as the original Chooz detector. The scintillator technology has improved as to allow the production of a Gadolinium-loaded scintillator that is very stable (on the timescale of years) allowing a longer run time of ∼ 5 years. The number of neutrinos detected in the far detector assuming 3 years of running will be ∼ 60,000 compared to ∼ 2,500 in the Chooz experiment, reducing the statistical error, 2.8% in Chooz, to 0.4%.

The aim is to reduce the systematic error, 2.7% in Chooz, to less than 0.6%. There are three sources of systematic error; the reactor, the detector and the analysis. With two detectors, each reactor component systematic; flux and cross-section, reactor power and energy per fission, reduce to below 0.1%. Making a relative measurement, between the two detectors, reduces many of detector systematics to similar orders.

The scintillators have been produced for both detectors in one batch, reducing the systematic on the number of H and Gd atoms in each detector. With a well performing scintillator the number of observed photons should be high enough such that all of the positron signal is observed so there is no systematic introduced by cutting on the positron spectrum.

In general, controlling the relative systematics between the two detectors is far easier than the absolute. Two detectors, however, introduces one new systematic—the live time, as both detectors must operate simultaneously.

6. – The far detector

Commissioning of the far detector began in early 2011 and ended in April 2011. Preliminary results show that the main design aims have been well achieved, with the detector operating with a lower energy threshold far below the commencement of the positron spectrum and a low event rate from radioactivity.

The first neutrino physics run began in April and ended in November 2011. Whilst the experiment is less sensitive without the near detector, it will still be more sensitive than the original CHOOZ detector. With data only from the first neutrino run we expect to obtain a sensitivity at least equal to the CHOOZ limit. With one year of data the experiment should be able reach a sensitivity to $\sin^2(2\theta_{13})$ of 0.06 with only the far detector.

7. – Conclusion

Double Chooz is the first next generation reactor experiment to commence operation. The construction of the far detector of the Double Chooz experiment was completed in 2010 with detector commissioning finishing in April 2011. The first phase of data-taking will occur with the far detector only. Figure 2 shows the improvement in sensitivity as a function of time; the far detector only phase and the two detector phase. Although the experiment is less sensitive without the near detector, only a few months of data are required to equal the sensitivity of the original CHOOZ detector and the experiment should reach a sensitivity to $\sin^2(2\theta_{13})$ of 0.06 with one year of data. With two detectors, Double Chooz will be able to measure $\sin^2(2\theta_{13})$ to 3σ if $\sin^2(2\theta_{13}) > 0.05$ or exclude $\sin^2(2\theta_{13})$ down to 0.03 at 90% for $\Delta m^2_{31} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$ with three years of data with both near and far detectors.

REFERENCES

[1] Schwetz T., *Phys. Lett. B*, **648** (2007) 54.

[2] Apollonio M. *et al.* (Chooz Collaboration), *Eur. Phys. J. C*, **27** (2003) 331.

[3] Mueller T. *et al.*, arXiv: 1101.2663.

[4] Mention G. *et al.*, *Phys. Rev. D*, **83** (2011) 073006.

[5] Ardellier F. *et al.* (Double Chooz Collaboration), Double Chooz: A search for the neutrino mixing angle θ_{13} (2006) preprint arXiv:hep-ex/0606025v4.

[6] Hamamatsu Corporation, `http://sales.hamamatsu.com/`.

[7] Hagner T. *et al.*, *Astropart. Phys.*, **14** (2000) 33.