Latest Double Chooz results

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Abstract. I report the latest results from the Double Chooz experiment on the $\theta_{13}$ neutrino mixing angle. Two detectors are located at distances of 400 m and 1050 m from the reactor cores of the Chooz nuclear power station (France) to measure the disappearance of electron antineutrinos. The far detector has been taking data since 2011, accumulating a live time of 467.90 days (66.5 GW-ton-year). In this article we focus on the latest measurement using neutrino-induced neutron capture on hydrogen. A new analysis improved the signal efficiency and reduced the backgrounds and systematic uncertainties, leading to $\sin^2 2\theta_{13} = 0.095^{+0.039}_{-0.038}$. When combined with the Gadolinium-based analysis this leads to $\sin^2 2\theta_{13} = 0.088^{+0.033}_{-0.033}$. The distortion from the prediction above a visible energy of 4 MeV is confirmed. The near detector started data taking in 2014 and first results shall be reported in 2016.

1. Introduction
In the standard three-flavor framework neutrino oscillations are described by two independent mass-squared differences, three mixing angles, and three (one related to CP-violation). All the parameters but the CP phases have been measured [1]. $\theta_{13}$ has been the last mixing angle measured by short-baseline reactor and long-baseline accelerator experiments [2, 3, 4, 5]. In the case of Double Chooz, the survival probability of electron antineutrino is well approximated by the two-flavor oscillation model:

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( 1.27 \frac{\Delta m^2_{31}[eV^2]L[m]}{E_{\nu}[MeV]} \right).$$ (1)

$\sin^2 2\theta_{13}$ is directly measured from the deficit and energy spectrum distortion in the electron antineutrino detected spectrum. In our analysis, $\Delta m^2_{31} = 2.44^{+0.09}_{-0.10} \times 10^{-3} eV^2$ [6], assuming the so-called normal neutrino mass hierarchy.

Antineutrinos are detected through the inverse beta-decay (IBD) process on free protons, $\bar{\nu}_e + p \rightarrow e^+ + n$, which provides two signals in coincidence: a prompt signal in the range of 1 - 10 MeV is given by the positron kinetic energy and the resulting $\gamma$s from its annihilation. This visible energy is related to the $\bar{\nu}_e$ energy by $E_{vis} \approx E_{\nu} - 0.8 MeV$. A delayed signal is given by the $\gamma$s released in the radiative capture of the neutron by a Gd or H nucleus. The results presented here focus on captures in Hydrogen, which occur after a mean time of 200 $\mu$s and release a total energy of 2.2 MeV, in the range of natural radioactivity energies.
2. The Detector

The main detector comprises four concentric cylindrical tanks filled with liquid scintillators or mineral oil. The innermost 8 mm thick transparent (UV to visible) acrylic vessel houses the 10 m$^3$ $\nu$-target liquid, a mixture of n-dodecane, PXE, PPO, bis-MSB and 1 g gadolinium/l as a beta-diketonate complex. The scintillator choice emphasizes radiopurity and long term stability. The $\nu$-target volume is surrounded by the $\gamma$-catcher, a 55 cm thick Gd-free liquid scintillator layer in a second 12 mm thick acrylic vessel, used to detect $\gamma$-rays escaping from the $\nu$-target. The light yield of the $\gamma$-catcher was chosen to provide identical photoelectron (pe) yield across these two layers. Outside the $\gamma$-catcher is the buffer, a 105 cm thick mineral oil layer. The buffer works as a shield to $\gamma$-rays from radioactivity of PMTs and from the surrounding rock and is one of the major improvements over the CHOOZ detector. It shields from radioactivity of photomultipliers (PMTs) and of the surrounding rock, and is one of the major improvements over the CHOOZ experiment. 390 10-inch PMTs are installed on the stainless steel buffer tank inner wall to collect light from the inner volumes. These three volumes and the PMTs constitute the inner detector (ID). Outside the ID, and optically separated from it, is a 50 cm thick inner veto liquid scintillator (IV). It is equipped with 78 8-inch PMTs and functions as a cosmic muon veto and as a shield to spallation neutrons produced outside the detector. The detector is surrounded by 15 cm of demagnetized steel to suppress external $\gamma$-rays. The main detector is covered by an outer veto system. The readout is triggered by custom energy sum electronics. The ID PMTs are separated into two groups of 195 PMTs uniformly distributed throughout the volume and the PMT signals in each group are summed. The signals of the IV PMTs are also summed. If any of the three sums is above a set energy threshold, the detector is read out with 500 MHz flash-ADC electronics and a deadtime-free acquisition system. Upon each trigger, a 256 ns interval of the waveforms of both ID and IV signals is recorded. Having reduced the ambient radioactivity enables us to set a low trigger rate (120 Hz) allowed the ID readout threshold to be set at 350 keV, well below the 1.02 MeV minimum energy of an IBD positron. The experiment is calibrated by several methods. A multi-wavelength LED–fiber light injection system (LI) produces fast light pulses illuminating the PMTs from fixed positions. Radio-isotopes $^{137}$Cs, $^{68}$Ge, $^{60}$Co, and $^{252}$Cf were deployed in the target along the vertical symmetry axis and, in the gamma catcher, through a rigid loop traversing the interior and passing along boundaries with the target and the buffer. The detector was monitored using spallation neutron captures on H.
and Gd, residual natural radioactivity, and daily LI runs. The energy response was found to be stable within 1% over time.

3. Previous Double Chooz Oscillation Analyses
The Double Chooz experiment first reported the observation of 8,249 candidate electron antineutrino events in 227.93 live days with 33.71 GW·ton-years (reactor power x detector mass x livetime) exposure using the inner 10.3 cubic meter fiducial volume target. The expectation in case of $\theta_{13} = 0$ was 8,937 events. The deficit is interpreted as evidence of electron antineutrino disappearance. From a rate plus spectral shape analysis we found $\sin^2 2\theta_{13} = 0.109 \pm 0.030$(stat) $\pm 0.025$(syst) [7]. In 2014 the collaboration improved those results leading to $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$ [2].

Double Chooz is unique among modern reactor-based neutrino experiments studying $\bar{\nu}_e$ disappearance in that data can be collected with all reactors off [8]. The collaboration reported data from 7.53 days of reactor-off running. Applying the same selection criteria as used in the Double Chooz reactor-on oscillation analysis, a measured background rate of $1.0 \pm 0.4$ events/day was obtained. The background model for accidents, cosmogenic $\beta$-n-emitting isotopes, fast neutrons from cosmic muons, and stopped-$\mu$ decays used in the oscillation analysis was therefore demonstrated to be correct within the uncertainties. A global fit to both $\theta_{13}$ and the total background can be performed by analyzing the observed neutrino rate as a function of the non-oscillated expected rate for different reactor power conditions. The result is fully consistent with the ones already published by Double Chooz [7, 9, 10].

4. The new Hydrogen Analysis
The Double Chooz experiment was the first to determine the value of the neutrino oscillation parameter $\theta_{13}$ from an analysis of inverse beta decay interactions with neutron capture on hydrogen [10]. This analysis uses a three times larger fiducial volume than the standard Double Chooz assessment, which is restricted to a region doped with gadolinium (Gd). The data sample used in this analysis is distinct from that of the Gd analysis, and the systematic uncertainties are also largely independent, with some exceptions, such as the reactor neutrino flux prediction. In the latest nH analysis [11], Double Chooz improves several important features of the analysis including mainly the energy reconstruction, the background reduction, the evaluation of systematics uncertainties.

The analysis improvements strongly rely on new background rejection methods, applying principally to the accidental background. An artificial neural network (ANN) has been developed, using the time difference between the prompt and delayed signals, distance difference and the delayed energy. The ANN is trained by using background samples from data and signal samples from Monte Carlo. The fast neutron background was reduced by applying a new technique using the pulse shape of each events. Indeed proton recoils from the fast neutron events can lead to a small shift on the pulse shape rising time that can be identified.

The detection systematics is carefully reevaluated by improving the determination of the fraction of events captured by hydrogen (using $^{252}$Cf and target neutrino events), the simulation of the spill in/out uncertainty (use of TRIPOLI-4 and GEANT4), and last but not least the evaluation of the free proton number in both target and gamma-catcher.

Finally two methods were used to extract the oscillation results. The first method is the reactor rate module (RRM). The reactors which generate the electron antineutrinos are binned in six reactor rate modes plus one reactor-off mode. By using these modes a fit relying on the rate-only information is performed. The second one is the spectral rate+shape fit, including relevant covariance matrices and pull terms. The pulls include background constraints, $\Delta m^2_{31}$, as well as the energy scale uncertainty. The RRM fit leads to $\sin^2(2\theta_{13})=0.095^{+0.038}_{-0.039}$. The rate+shape fit leads to $\sin^2(2\theta_{13})=0.124^{+0.030}_{-0.039}$. These results, displayed in fig. 2 are consistent
Figure 2. Left: Observed rate vs reactor flux dependent expected rate and best fit (dotted line) using as input the background estimate and the reactor off data. The dotted line is the no-oscillation expectation. Right: The ratio of the IBD candidates visible energy distribution, after background subtraction, to the corresponding distribution expected in the no-oscillation hypothesis. The red points and band are for the hydrogen capture data and its systematic uncertainty described in this publication and the blue points and band are from the Gd capture data. Red solid line show the best fit from the R+S analysis.

with previous Double Chooz results based on neutron capture on hydrogen [10]. Note that the spectrum distortion above 4 MeV is observed and has similar feature as previously reported [2]. Nevertheless it does not affect the oscillation results.

5. Conclusions
The Double Chooz reported a new analysis based on neutron capture on hydrogen capture. This leads to improved results [10], consistent with previous analyses. Based on 462.72 days of data, a value of $\sin^2 2\theta_{13} = 0.095^{+0.039}_{-0.038}$ is being determined. When combined with the Gadolinium-based analysis this leads to $\sin^2 2\theta_{13} = 0.088^{+0.033}_{-0.033}$. The near detector is now operating in data taking mode since 2014. First results with two detectors are expected by middle of 2016. With both detectors, the sensitivity to $\theta_{13}$ is expected to improve significantly due to the cancellation of reactor induced systematics.

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