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Double Chooz: Latest results

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Abstract

The latest results from the Double Chooz experiment on the neutrino mixing angle θ_{13} are presented. A detector located at an average distance of 1050 m from the two reactor cores of the Chooz nuclear power plant has accumulated a live time of 467.90 days, corresponding to an exposure of 66.5 GW-ton-year (reactor power × detector mass × live time). A revised analysis has boosted the signal efficiency and reduced the backgrounds and systematic uncertainties compared to previous publications, paving the way for the two detector phase. The measured $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$ is extracted from a fit to the energy spectrum. A deviation from the prediction above a visible energy of 4 MeV is found, being consistent with an unaccounted reactor flux effect, which does not affect the θ_{13} result. A consistent value of θ_{13} is measured in a rate-only fit to the number of observed candidates as a function of the reactor power, confirming the robustness of the result.

Keywords: reactor, neutrino, oscillation, θ_{13}

1. Introduction

Neutrino oscillations in the standard three-flavor framework are described by three mixing angles, three mass-squared differences (two of which are independent) and one CP-violating phase. Excepting the phase which still remains unknown, all the other parameters have been measured [1]. θ_{13} was the last to be measured by short-baseline reactor and long-baseline accelerator experiments [2, 3, 4, 5, 6, 7, 8, 9].

For the energies and distances relevant to Double Chooz, the oscillation probability is well approximated by the two-flavor case. Thus, the survival probability reads:

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m^2_{31}[\mathrm{eV}^2] L[\mathrm{m}]}{E_\nu[\mathrm{MeV}]} \right) \quad (1)$$

So θ_{13} can be measured from the deficit in the electron antineutrino flux emitted by the reactors. In this analysis, $\Delta m^2_{31} = 2.44^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$, taken from [10], assuming normal hierarchy .

Antineutrinos are detected through the inverse beta-decay (IBD) process on protons, $\overline{\nu}_e + p \to e^+ + n$, which provides two signals: a prompt signal in the range of 1 - 10 MeV is given by the positron kinetic energy and the resulting γs from its annihilation. This visible energy is related to the $\overline{\nu}_e$ energy by $E_{vis} \approx E_\nu - 0.8\,\mathrm{MeV}$. A delayed signal is given by the γs released in the radiative capture of the neutron by a Gd or H nucleus. The results presented here correspond only to captures in Gd, which occur after a mean time of 31.1 μs and release a total energy of 8 MeV, which is far above the natural radioactivity energies. The coincidence of these two signals grants the experiment a powerful background suppression.

2. The Double Chooz experiment

Double Chooz (DC) is a 2-detector experiment located in the surroundings of the Chooz nuclear power plant (France), which has two pressurized water reactor cores, producing 4.25 $\mathrm{GW_{th}}$ each. The Near Detector (ND), placed at ∼ 400 m from the cores, has a 120 m.w.e. overburden and it is currently being commissioned. The Far Detector (FD), placed at ∼ 1050 m from

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the cores, has a 300 m.w.e. overburden and its data are used here. The 2-detector concept allows to extract θ_{13} with high precision from the relative comparison of the $\overline{\nu}_e$ flux at the two detectors. Because the detectors are built identical, all the correlated uncertainties between them are cancelled.

Since the ND was not operative for this analysis yet, an accurate reactor flux simulation was needed to obtain the $\overline{\nu}_e$ prediction. Électricité de France provides the instantaneous thermal power of each reactor, and the location and initial composition of the reactor fuel. The simulation of the evolution of the fission rates and the associated uncertainties is done with `MURE` [11, 12], which has been benchmarked with another code [13]. The reference $\overline{\nu}_e$ spectra for ^{235}U, ^{239}Pu and ^{241}Pu are computed from their β spectrum [14, 15, 16], while [17] is used for ^{238}U for the first time. The short-baseline Bugey4 $\overline{\nu}_e$ rate measurement [18] is used to suppress the normalization uncertainty on the $\overline{\nu}_e$ prediction, correcting for the different fuel composition in the two experiments. The systematic uncertainty on the $\overline{\nu}_e$ rate amounts to 1.7%, dominated by the 1.4% of the Bugey4 measurement. Had the Bugey4 measurement not been included, the uncertainty would have been 2.8%.

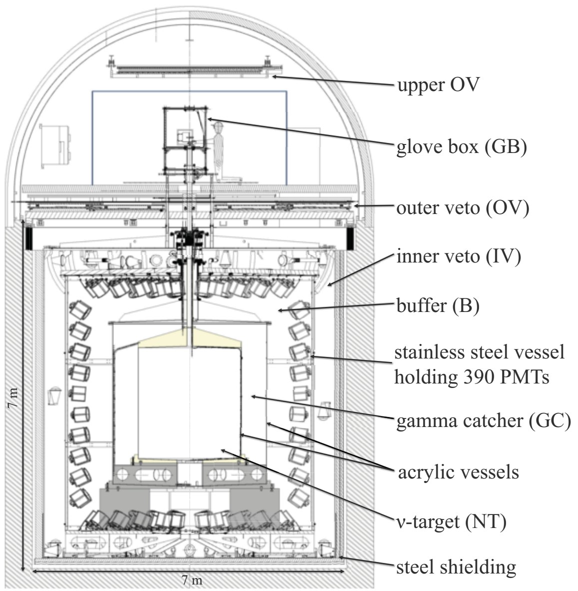

Figure 1: Double Chooz far detector design.

The DC detector is composed of four concentrical cylindrical vessels (see figure 1). The innermost volume, the ν-target (NT), is an 8 mm thick acrylic vessel (UV to visible transparent) filled with 10.3 m^3 of liquid scintillator loaded with Gd (1g/l) to enhance the neutron captures. The γ-catcher (GC), a 55 cm thick layer of liquid scintillator (Gd-free) enclosed in a 12 mm thick acrylic vessel surrounds the NT to maximize the energy containment. Surrounding the GC is the buffer, a 105 cm thick layer of mineral oil (non-scintillating) contained in a stainless steel tank where 390 low background 10-inch photomultiplier tubes (PMT) are installed, and which shields from the radioactivity of the PMTs and the surrounding rock. The elements described so far constitute the inner detector (ID). Enclosing the ID and optically separated from it, the inner veto (IV), a 50 cm thick layer of liquid scintillator, serves as a cosmic muon veto and as an active shield to incoming fast neutrons observed by 78 8-inch PMTs positioned on its walls. A 15 cm thick demagnetized steel shield protects the whole detector from external γ-rays. The outer veto (OV), two orthogonally aligned layers of plastic scintillator strips placed on top of the detector, allows a 2D reconstruction of impinging muons. An upper OV covers the chimney, which is used for filling the volumes and for the insertion of calibration sources (encapsulated radioactive sources of ^{137}Cs, ^{68}Ge, ^{60}Co and ^{252}Cf and a laser). Attached to the ID and IV PMTs, a multi-wavelength LED-fiber light injection system is used to periodically calibrate the readout electronics.

Waveforms from all ID and IV PMTs are digitized and recorded by dead-time free flash-ADC electronics.

DC has pioneered the measurement of θ_{13} using the $\overline{\nu}_e$ spectral information because of its exhaustive treatment of the energy scale, which is applied in parallel to the recorded data and the Monte Carlo (MC) simulation. A linearized photoelectron (PE) calibration produces a PE number in each PMT which has been corrected from dependencies on the gain non-linearity and time. A uniformity calibration corrects for the spatial dependence of the PE, equalizing the response within the detector. The conversion from PE to energy units is obtained from the analysis of neutron captures in H from a ^{252}Cf calibration source deployed at the center of the detector. A stability calibration is applied to the data to remove the remaining time variation by analyzing the evolution of the H capture peak from spallation neutrons, which is also crosschecked at different energies using the Gd capture peak and the α decays of ^{212}Po. Two further calibrations are applied to the MC to correct for the energy non-linearity relative to the data: the first is applied to every event and it arises from the modeling of the readout systems and the charge integration algorithm; the second, which is only applied to positrons, is associated to the scintillator modeling. The total systematic uncertainty in the energy scale amounts to 0.74%, improving