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Double Chooz: new results on the θ_{13} mixing angle

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The Double Chooz experiment aims at a precise measurement of the neutrino mixing angle θ_{13} by measuring a reactor antineutrino flux at two different sites. A first detector located ∼1km away from the two cores of the nuclear power plant of Chooz (France) has been operated since early 2011. The second detector (∼400m away) is under construction and will start operation in 2013. Double Chooz presented in November 2011 a first indication of reactor electron antineutrino disappearance consistent with neutrino oscillations. The observed deficit in the neutrino rate, along with the distortion of the neutrino energy spectrum, was interpreted as a consequence of the oscillation driven by the mixing angle θ_{13}. In 2012, a second analysis has been performed by the Double Chooz collaboration after 250 days of data taking confirming the oscillation effect and providing a more accurate best-fit value for the θ_{13} angle. 8249 candidate electron antineutrino events are observed in 227.93 live days, while the expectation in case of θ_{13}=0 is 8937 events. From a rate plus spectral shape analysis, $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$ is found. The reliability of the background model used in the oscillation analysis has been validated by means of 7 days of reactor-off data taken during two different periods, from which a total background measurement has been obtained: 1.0±0.4 events/day.

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1. Reactor neutrinos and the last mixing angle

Within the three neutrino paradigm, the neutrino oscillation probability can be described by three mixing angles (θ_{12},θ_{23},θ_{13}), two independent mass square differences (Δm_{21},Δm_{31}), and one phase δ_{CP} responsible for the CP-violation in the leptonic sector. While the dominant oscillations driven by θ_{12} and θ_{23} (the so-called solar and atmospheric sectors) have been measured by different experiments [1], the so-called interference sector driven by the mixing angle θ_{13} remained unrevealed until very recently. The first direct indications of a non-zero value of this mixing angle has come from the accelerator-based experiments MINOS [2] and T2K [3]. However, accelerator neutrino experiments cannot measure θ_{13} independently of the value of δ_{CP}, which is unknown. Therefore, reactor neutrino experiments stand as the optimal way to provide an accurate value of θ_{13}. In the two flavors scheme and for short baselines (L$\sim$km), the survival probability of the electron anti-neutrinos $\bar{\nu}_e$ with energy E_ν generated at nuclear reactor cores can be described as:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2(\frac{1.27\Delta m^2_{31}(\mathrm{eV}^2)L(\mathrm{m})}{E_\nu(\mathrm{MeV})}) \tag{1.1}$$

which do not depend on δ_{CP}. The value of θ_{13} can be measured directly from the oscillation amplitude, inferred from an energy-dependent deficit in the number of observed neutrinos. These are detected via the so-called inverse beta decay (IBD) $\bar{\nu}_e + p \to n + e^+$. When this reaction takes place in liquid scintillator doped with Gadolinium, it produces two signals separated by about μs: the first one due to the e^+ and its annihilation (prompt signal), and the second one due to the n capture in a Gd nucleus (delayed signal). This characteristic signature yields a very efficient background rejection.

2. The Double Chooz experiment

The Double Chooz (DC) experiment, located at the nuclear power plant of Chooz (France), aims at providing and accurate and precise value of θ_{13} by means of a long-term stability multi-detector setup. The Chooz nuclear plant consists of two cores yielding a total thermal power of 8.54 GW$_{th}$. The DC far detector is placed 1050 m away from the cores, close to the maximal oscillation distance and providing shielding (300 m.w.e.) against cosmic rays. A second identical detector (near detector, in construction) will be installed 400 m away from the reactor cores, in a new laboratory (115 m.w.e).

The DC detectors design is optimized to reduce backgrounds. The far detector, shown in Fig. 1, consist of a set of concentric cylinders and an outer muon veto on the top. The innermost volume (*neutrino target or NT*) contains 8.3 tons of Gd-loaded (0.1%) liquid scintillator inside a transparent acrylic vessel, where the neutrinos interact via the IBD process. This volume is surrounded by another acrylic vessel filled with unloaded scintillator (*gamma-catcher or GC*). This second volume is meant to fully contain the energy deposition of gamma rays from the neutron capture on Gd and the positron annihilation in the target region. The GC is in turn contained within a third volume (*buffer tank*) made of stainless steel and filled with mineral oil. This volume acts as a shield against the radioactivity from the photomultiplier tubes (PMTs), meant to detect the scintillator light, and the surrounding rock. The surface of the buffer is covered with an array of

390 low background 10-inch PMTs. Some of these PMTs are observed to emit light from their base circuit, causing false triggers hereafter referred to as light noise (LN). The NT, GC and buffer tank define the *inner detector* (ID). The ID is surrounded by the *inner muon veto* (IV), a 50 cm thick liquid scintillator volume equipped with 78 8-inch PMTs. Both ID and IV are in turn surrounded by 15 cm thick steel shield. Finally, the upper part of the detector is covered by an outer muon veto (OV), consisting of plastic scintillator strips grouped in different modules. The OV modules are placed over the main detector.

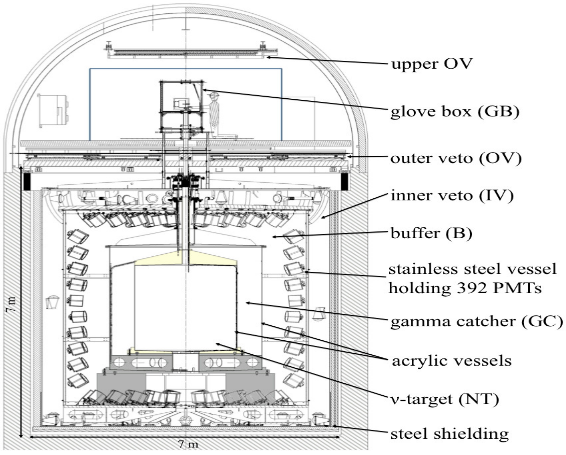

Figure 1: The Double Chooz detector.

The detector performance is analyzed by means of a redundant set of calibration systems, so the systematic uncertainties related to the detector response are suppressed. A multi-wavelength LED-fiber system (LI) is used to characterize the PMTs, as well as to monitor the stability. Radioactive sources (^{68}Ge, ^{137}Cs, ^{60}Co and ^{252}Cf) are deployed through the glove box into the NT and the GC to measure the neutrino detection efficiency and to reduce the systematics in the energy scale. Furthermore, the detector stability is monitored by means of spallation neutron captures on H and Gd. The energy response is found to be stable within 1%, and no significant decrease due to degradation of liquid scintillator has been observed.

The dominant backgrounds in DC are 1) accidental coincidences of β decays followed by a neutron-like signals; 2) cosmic muon spallation products (β-n emitters, namely^{9}Li and ^{8}He), which emit a n immediately following the β-decay process; 3) stopping muons (μ) and the subsequent Michel electrons; 4) fast neutrons, produced by muons in the surrounding rock, which enter the detector.

The DC experiment started the physics data taking in April 2011 with the far detector. The collaboration published its first results in November 2011 with 15.34 GW-ton-years of exposure [4]: this has been the first indication of a non-zero value of θ_{13} provided by a reactor-based experiment. As off 2012, DC has published an updated analysis on θ_{13} with an additional 18.37 GW-ton-years data [5].

3. New results on θ_{13}

The current analysis (hereafter DC-2012 analysis) has been improved with respect to [4] (DC-2011 analysis) by means of a better energy reconstruction, an additional muon veto, and the use of the OV. The systematics in the energy reconstruction have been reduced by addressing the PMT gain non-linearity, and by applying position dependence and time stability corrections. The total systematic uncertainty in the energy scale is 1.13%. As in the DC-2011 analysis, the IBD candidates are extracted from a sample of triggers above 0.5 MeV, not tagged as LN and at least 1 ms away from the last tagged muon. The selection then applies four cuts to the prompt and delayed IBD signals: 1) prompt trigger: $0.7 < E_{\mathrm{prompt}} < 12.2$ MeV; 2) delayed trigger: $6.0 < E_n < 12.0$ MeV (left panel in Fig. 2); 3) time difference: $2\ \mu\mathrm{s} < \Delta t_{\mathrm{prompt}/delayed} < 100\ \mu\mathrm{s}$ (right panel in Fig. 2); 4) multiplicity: no additional valid triggers from 100 μs preceding the prompt signal to 400 μs after it. In the current DC-2012 analysis, the selection further rejects candidates according to two more conditions: 5) cosmogenic β-n background reduction: candidates within a 0.5 s window after a muon depositing high energy (>600 MeV) crosses the ID ("showering-μ veto"); 6) μ/fast-n background reduction: candidates whose prompt signal is coincident with an OV signal (OV veto).

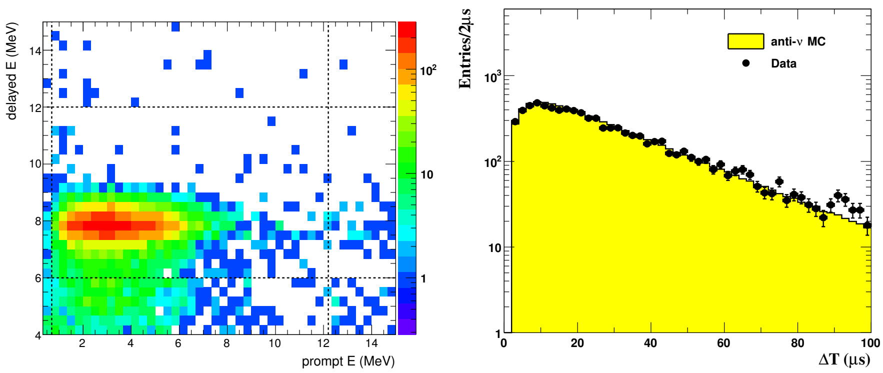

Figure 2: Correlation between the prompt and delayed signals of the $\bar{\nu}_e$ candidates. Left: E_{delayed} vs E_{prompt} (dashed lines show the cuts applied). Right: time difference.

A sample of 8249 candidates have been observed in 227.93 days live-time after all IBD selection criteria are applied. 8936.8 events are expected in absence of neutrino oscillation, once the background is accounted for. The rate and the spectrum shape of the accidental background is precisely measured by applying the same IBD selection criteria but using coincidence window shifted by 1 s in order. The statistics of the data sample is increased by using multiple windows with intervals of 500 μs. The accidental background rate is then estimated to be 0.261 ± 0.02 events/day. The rate and spectrum of the ^{9}Li and ^{8}He background are analyzed by means of the time and spatial correlation with their parent muons. The overall rate of this cosmogenic background is found to be 1.25 ± 0.54 events/day from a fit to the time difference between the muon and $\bar{\nu}_e$ candidates. Due to the lack of statistics, the energy spectrum is estimated from MC, although data are used to cross-check the reliability of the simulation. Finally, the fast neutron and the stopping muon backgrounds are treated in a combined way, as correlated background. Fast neutron background is studied using events tagged by the IV and the OV. The contribution of stopping muons is estimated using events tagged by the OV, or with a delayed energy between 20 and 60 MeV. The total rate of these backgrounds is found to be 0.67$\pm$0.20 events/day. The combined energy shape is fit to a linear model, yielding a small negative slope, although consistent within 1σ with a flat distribution. Taking into account all the contributions above, the total background rate is estimated to be 2.2$\pm$0.6 events/day. Left panel of Fig. 3 shows the observed rate per day of $\bar{\nu}_e$ candidates as a function of the expected rate, where the oscillation effect is clearly visible. The extrapolation of the fit to zero expectation provides an independent measurement of the total background rate: 2.9$\pm$1.1 events/day, in very good agreement with the above estimate.

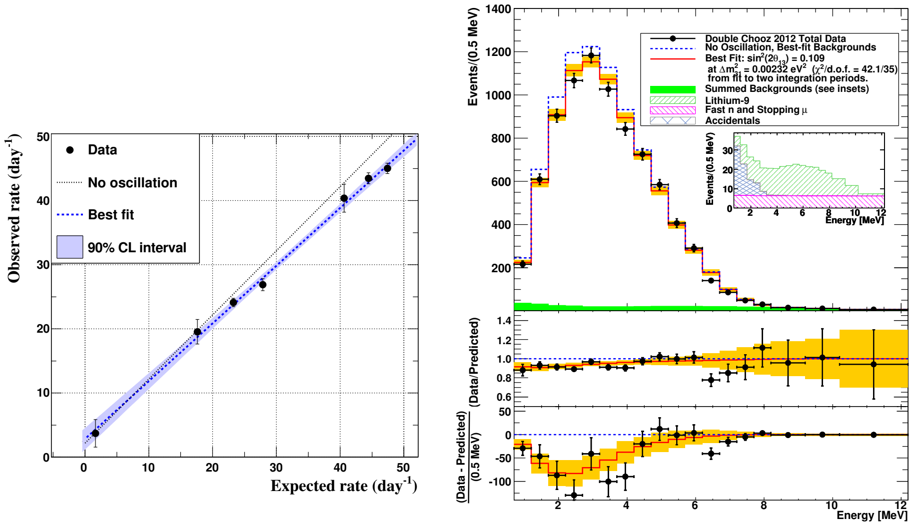

Figure 3: Left: Observed rate per day of IBD candidates as a function of the expected rate. Right: Observed energy spectrum (points) superimposed on the prediction with no-oscillation (dashed line) and the best-fit prediction with oscillation (solid line with uncertainty) including the background contributions shown in inset.

The observed deficit of $\bar{\nu}_e$ candidates is interpreted as evidence of reactor neutrino oscillation driven by a non-zero value of θ_{13}. The oscillation analysis is based on a combined chi^2 fit to both anti-neutrino rate and shape, assuming a two flavor scenario. The data set is divided into two integration periods based on the reactor power (one when reactor is operating at 20% of its nominal power, and another when both reactors are above 20%), resulting in different signal to background ratio, so backgrounds are better constrained in the fit. Systematic and statistical uncertainties are propagated to the fit by the use of a covariance matrix, although pulls accounting for the uncertainty in the cosmogenics and correlated background rates, the energy scale, and Δm^2_{31} are introduced in the chi^2. The main systematics are those on the predicted reactor flux (1.67%), on the cosmogenic background (1.38%) and on the detection efficiency (0.95%); acounting for the statiscal error (1.06%), the total normalization uncertanty is 2.66%. The best-fit was found at $\sin^2 2\theta_{13}$ = 0.109$\pm$0.030(stat.) $\pm$ 0.025(syst.) with χ^2_{min}/d.o.f = 42.1/35. The best-fit values of the systematic error parameters were consistent with the estimated uncertainties. The observed energy spectrum and the best-fit prediction are shown in right panel of Fig. 3 (both integration periods added). Confidence intervals were determined using a frequentist technique. The allowed region at 68%(90%)

CL is $0.067(0.043) < \sin^2 2\theta_{13} < 0.15(0.18)$, and the no-oscillation hypothesis is excluded at 99.8% (2.9σ).

4. Direct background measurement

Among ongoing reactor-based oscillation experiments, DC is unique in obtaining a *reactor-off* data set when the two cores of the Chooz site are both brought down for maintenance. As off 2012, DC has taken 7.53 days of reactor-off data, in two different periods. A direct measurement of the backgrounds in the oscillation analyses is performed by applying the same $\bar{\nu}_e$ selection criteria to this data sample [6]. The application of the $\bar{\nu}_e$ selection cuts to the reactor-off data sample yields 21 (8) $\bar{\nu}_e$ candidates in the DC-2011 (DC-2012) analysis. The DC-2012 analysis vetoes five events using the showering-μ veto (β-n-like events), and another eight using the OV veto (μ/fast-n-like events). Fig. 4 shows the prompt energy distribution of the candidates, superimposed on the expected spectra of background events and residual neutrinos. Once the expected number of detected residual neutrinos is subtracted, these numbers yield a measured total background of 2.7 ± 0.6 events/day (1.0 ± 0.4 events/day) using DC-2011 (DC-2012). This result is consistent with the background estimates for this specific period: 3.4 ± 0.6 (2.0 ± 0.6). This confirms the reliability of the background model used in the oscillation analysis.

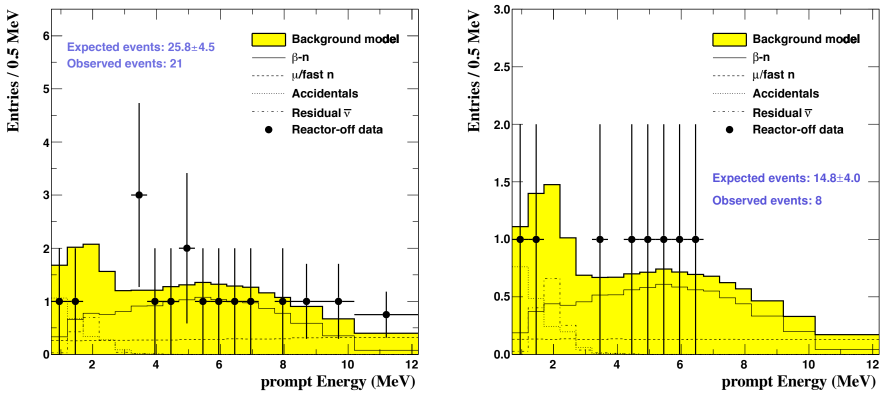

Figure 4: $\bar{\nu}_e$ candidates in the reactor-off data sample, with breakdown by components. Top and bottom figures show DC-2011 and DC-2012 selection results, respectively.

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