



New results from the Double Chooz experiment

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Abstract

The Double Chooz experiment presents new results derived from data collected during 467.90 live days in a detector located 1050 m from two reactor cores at the Chooz Nuclear Power Plant. This improved θ_{13} oscillation analysis relies on new techniques for reducing backgrounds and systematic uncertainties while increasing $\bar{\nu}_e$ signal efficiency. In a fit to the observed $\bar{\nu}_e$ rate and energy spectrum, the value of θ_{13} is measured to be $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$. A consistent and uniquely background-independent result, $\sin^2 2\theta_{13} = 0.060 \pm 0.039$, is obtained with a reactor rate modulation approach. While the precision of these results is still limited by reactor flux uncertainty, these analyses demonstrate powerful techniques which will reach their full potential when the second Double Chooz detector begins operation. In addition to the oscillation results, deviations from the reactor $\bar{\nu}_e$ prediction observed above a 4 MeV are reported.

Keywords: reactor neutrino oscillation θ_{13}

1. The Double Chooz experiment

Double Chooz is a reactor antineutrino experiment designed to measure the mixing angle θ_{13} with a final precision of around 10%. It consists of two identical detectors located 1050 m (far detector, FD) and 409 m (near detector, ND) from the two cores of the nuclear power plant in Chooz, France. As the near detector is not yet operational, oscillation analyses are performed by comparing far detector data to a simulated reactor flux. Following the first indication of a non-vanishing value of θ_{13} [1], a $\sim 3\sigma$ measurement [2], and a first background-independent result [3], the collaboration now reports improved measurements of the mixing angle. The most recent oscillation analyses use a sample of 17351 $\bar{\nu}_e$ candidates collected in 460.67 days of data-taking. The corresponding prediction for signal and backgrounds is 18300^{+370}_{-330} events.

2. Latest oscillation analyses

The new analyses are built upon the $\bar{\nu}_e$ candidate selection described in [4], which targets inverse beta

decay (IBD) interactions followed by a neutron capture on Gd. Compared to previous analyses, new variables and optimized cuts have increased signal detection efficiency and decreased associated systematic errors while simultaneously reducing background rates and uncertainties. The new selection has reduced the total detection uncertainty to 0.63%. The background contamination in the $\bar{\nu}_e$ sample has been reduced to 0.070 ± 0.005 events/day from accidental coincidences, 0.67 ± 0.20 events/day from fast neutrons and stopping muons, and $0.97^{+0.41}_{-0.16}$ events/day from the decay of cosmogenic isotopes. The detector energy scale has also been significantly improved. Reactor flux uncertainty (1.7%) remains the dominant systematic error.

The value of $\sin^2 2\theta_{13}$ has been derived from two complementary approaches: a fit to the rate and energy spectrum of the prompt IBD signals (R+S), and a reactor rate modulation (RRM) fit, as described in [3]. Both techniques take advantage of 7.24 live days taken when both reactors were off as a constraint on the total background rate. The *Rate+Shape* analysis is a comparison of prompt signals in the energy spectrum of the

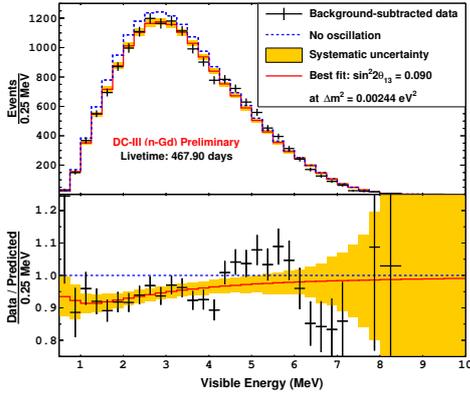


Figure 1: Background-subtracted data (black points, with statistical error bars) superimposed upon best-fit (red line) and no oscillation (blue dashed line) signal, with systematic errors in each bin (gold bands). Top: Positron energy spectrum. Bottom: Ratio of data to prediction.

observed IBD candidates and a Monte Carlo prediction. The value of $\sin^2 2\theta_{13}$ is obtained by minimizing a χ^2 which includes nuisance parameters (pull parameters) to account for uncertainties on background rates, energy scale, and other factors. Covariance matrices account for uncertainties in detection efficiency, background spectrum shape, and the reactor flux model. The minimum χ^2 value, $\chi^2_{\min}/d.o.f. = 52.2/40$, occurs at $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$, where the uncertainty interval covers $\chi^2 < \chi^2_{\min} + 1.0$. Figure 1 shows the prompt spectrum of the data and best fit MC, along with ratio of the data to the no-oscillation prediction, after subtraction of backgrounds. The best-fit values of the background rates are summarized in Table 1.

Background type	Input Rate (d^{-1})	Best-fit Rate
Li+He	$0.97^{+0.41}_{-0.16}$	0.74 ± 0.13
Fast-n + stop- μ	0.604 ± 0.051	$0.568^{+0.038}_{-0.037}$
Accidental	0.0701 ± 0.0026	0.0703 ± 0.0026

Table 1: Input values and uncertainties for rates of backgrounds in the oscillation analysis. Best-fit values and their errors are the output of the *Rate + Shape* fit.

The RRM analysis relies on the dependence of $\bar{\nu}_e$ signal rate, and independence of background rates, on reactor power. By comparing the observed and expected IBD candidate rates, both θ_{13} and the total background rate (B) are simultaneously extracted. A χ^2 scan in $\sin^2 2\theta_{13}$ and B is carried out, yielding the best-fit values of $\sin^2 2\theta_{13} = 0.060 \pm 0.039$ and $B = 0.93^{+0.43}_{-0.36}$, with $\chi^2_{\min}/d.o.f. = 4.2/6$. This result is fully consis-

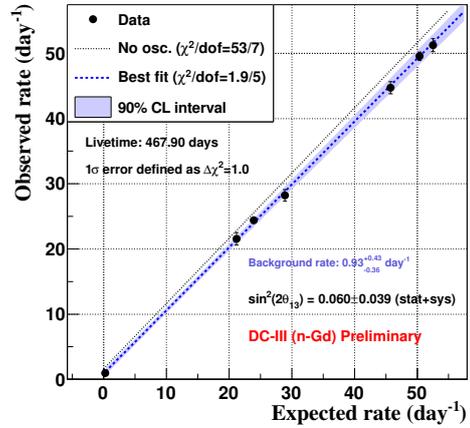


Figure 2: Ratio of observed rate to rate expected with no oscillation (black dots) superimposed upon best fit (dashed blue line). Fit includes reactor-off data. Black dotted line shows the null hypothesis of observed rate equal to expected no-oscillation rate.

tent with the R+S result. Figure 2 shows the correlation of the expected and observed IBD candidate rate along with the best-fit prediction. Because the RRM approach does not involve any *a priori* assumptions about backgrounds, this θ_{13} measurement is background model-independent. However, the background model used in the R+S fit can be added as an input, providing an additional constraining on B and improving the precision on the mixing angle. A fit including the background model in this way yields $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$.

3. Energy spectrum distortion

In Figure 1, an energy-dependent deficit is clearly visible in the data below 4 MeV, consistent with the expectation for reactor neutrino oscillation. Meanwhile, additional spectrum distortion is visible above 4 MeV, which can be characterized by an excess around 5 MeV and deficit around 7 MeV. The presence of these features, which lie outside the main oscillation signal region, has been shown to negligibly impact θ_{13} . Several studies have been carried out to investigate their origin. These studies disfavor detector-related explanations, such as an energy scale distortion or previously unidentified background. However, a clear correlation of the excess with the reactor power has been observed in [4]. Consequently, the most likely explanation for the spectrum deviations is that the reactor flux has not been predicted accurately in this region. In an RRM fit in which both $\sin^2 2\theta_{13}$ and the total background rate are

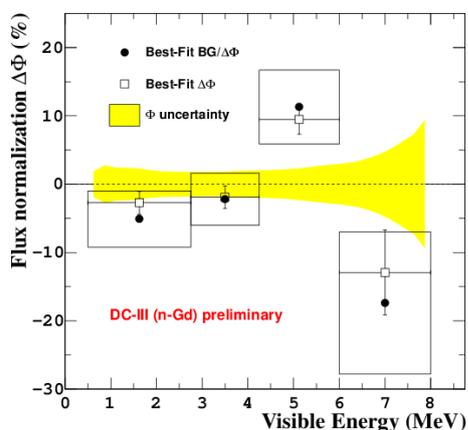


Figure 3: Best-fit reactor flux normalization from independent RRM fits (4 energy regions) with an additional constraint on $\sin^2 2\theta_{13}$. Empty squares and solid points show the best-fit normalization values with respect to the prediction with and without a constraint in the background, respectively. The yellow band shows the uncertainty in the reactor flux prediction.

constrained, the best-fit value of the flux normalization is in 3σ disagreement with the reactor flux prediction in the energy range from 4.25 to 6.0 MeV. Figure 3 shows the best-fit flux normalization values (with respect to prediction) for four different energy ranges, with and without the background constraint.

4. Future precision

The ND will begin operation in 2014. Data from this detector will strongly suppress reactor flux uncertainty, currently the dominant contribution to uncertainty on $\sin^2 2\theta_{13}$. Figure 4 shows projected sensitivity with the ND based on the systematic uncertainties of the current analysis. Background rates in the ND are scaled from the FD based on measured muon rates. Sensitivity projections use these additional assumptions: 0.2% uncertainty on the relative detection efficiency between the FD and ND; 0.1% uncorrelated uncertainty in reactor flux; totally uncorrelated energy scale and background rate errors. In the sensitivity plot, the shaded region represents the range of potential improvements achievable through continued reduction of systematic errors. The lower edge of the shaded region designates sensitivity with no systematic uncertainties beyond reactor flux. The projected sensitivity with the ND reaches $\sigma(\sin^2 2\theta_{13}) = 0.014$ based on current systematics and could be reach 0.010 with future analysis improvements. An alternative curve in Fig. 4 shows sensi-

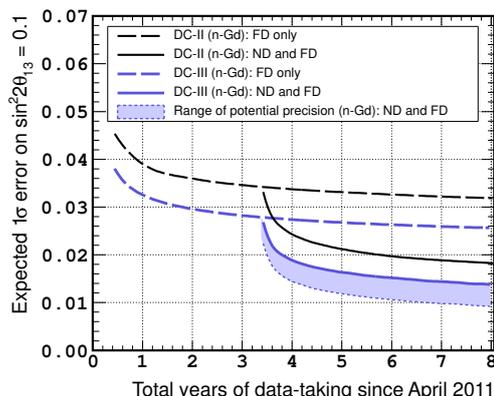


Figure 4: Projected Double Chooz precision from the R+S fit. Blue (black) curves use same systematics, live-to-calendar time ratio, and far detector backgrounds as the present analysis (previous Gd-based analysis [2]). Shaded blue region represents potential future precision, depending on reduction of systematic errors

tivity based on the analysis reported in [2] and emphasizes the significant advances made in the present analysis. Figure 4 includes data only from the Gd capture channel, and sensitivity will be further enhanced with data from a H capture analysis, currently in progress.

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