Entering the Two-Detector Phase of the Double Chooz Experiment

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In recent years, observations of electron antineutrino disappearance at nuclear reactor sites have yielded increasingly precise measurements of the neutrino mixing parameter θ_{13}. Two experiments, Daya Bay and RENO, have made such measurements by comparing the antineutrino signal observed approximately 1 km from reactor cores to the essentially unoscillated signal observed in near detectors, a few hundred meters from the cores. Meanwhile, the Double Chooz experiment has produced multiple θ_{13} measurements using only a far detector and reactor flux simulations. Now, as the first months of data are taken with the Double Chooz near detector, the experiment is poised to produce its most precise precise θ_{13} measurements yet. The near detector will also provide rich opportunities to study the reactor antineutrino flux and possible sterile neutrino signatures. This report reviews the latest single-detector analyses from Double Chooz and discusses prospects for the newly inaugurated two-detector phase.

1 Reactor-based measurements of θ_{13}

1.1 Motivation

By 2010, the three-neutrino mixing paradigm had been well established, and many of its parameters had been measured. The magnitudes of the three mass splittings were known, along with two of the three mixing angles. A remaining question was the size third mixing angle, θ_{13}. The CHOOZ experiment indicated this angle was small,[1] but its exact magnitude, including whether it could be distinguished from zero, was not known.

Measuring θ_{13} has important implications for the neutrino sector, and perhaps beyond it. To some extent, the size of this mixing angle sets the difficulty level for determining the neutrino mass hierarchy and measuring the CP-violating phase, δ. More basically, θ_{13} must be nonzero for CP violation to appear in neutrino oscillations. The value of θ_{13} may also provide some insight into the structure of neutrino mixing matrix, which differs dramatically from the analogous CKM matrix in quarks. All of these issues may relate to deeper problems, including the nature of neutrino mass, the baryon asymmetry of the universe, and the origin of flavor.

1.2 Method

The energies and flavor compositions of typical neutrino sources, and the sizes of the relevant mass splittings, present two practical channels for measuring θ_{13}. One is a search for electron neutrino appearance in a muon neutrino beam. The probability of this transition depends on many parameters besides θ_{13}, including both other mixing angles, the sign of Δm^2_{31}, and δ; for sufficiently long baselines, it also involves matter effects. While these dependencies give the $\nu_\mu \to \nu_e$ a broad physics reach, they preclude a straightforward measurement of θ_{13}.

An alternative channel for measuring θ_{13} is the disappearance of electron antineutrinos generated in the beta decays of nuclear fission products. In this context, $\bar{\nu}_e$ survival probability is a simple expression depending only on θ_{13} and one oscillatory phase. For a $\bar{\nu}_e$ of energy E, traveling a distance L between generation and detection, the survival probability[a] is:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right) \tag{1}$$

Given the measured value[2] of $\Delta m^2_{31} \approx 0.0024$ eV^2 and average reactor antineutrino energy of $\sim$ 4 MeV, the first oscillation maximum occurs $\sim$ 2 km from the reactor cores. Therefore, the oscillation probability, and hence $\sin^2 2\theta_{13}$, can be measured by comparing the rate and/or spectral shape of the $\bar{\nu}_e$ signal observed $\sim 1-2$ km from the reactors to the unoscillated flux. The latter may be measured, by observing the $\bar{\nu}_e$ signal a few hundred meters or less from the reactors, or predicted through a reactor simulation. Such simulations depend on semi-empirical calculations of the $\bar{\nu}_e$ emitted by reactors, which have significant normalization and shape uncertainties. Combined with the other uncertainties involved in a reactor flux simulation, these are strong limitations on the precision of single-detector θ_{13} measurements. A near detector, which directly measures the unoscillated reactor antineutrino flux, is required to achieve percent-level precision on $\sin^2 2\theta_{13}$.

2 Double Chooz measurements

2.1 Experiment design

The Double Chooz experiment is located at the Chooz Nuclear Power Plant in the Champagne-Ardenne region of France. The power station hosts two pressurized water reactors, each with a nominal power of 4.25 GW$_{th}$. The far detector, which began operation in 2011, is located 1050 m from the reactors, in a cavern with 300 m.w.e. overburden. The near detector, which was completed in late 2014, is located 400 m from the reactors, under a 140 m.w.e. overburden.

The detectors were designed to efficiently observe the inverse beta decay (IBD) interaction, $\bar{\nu}_e + p \to e^+ + n$. The positron is detected in liquid scintillator via its ionization track and annihilation, which together deposit $E_{vis} \approx E_\nu - 0.8$ MeV. The neutron is detected when it is absorbed by a nucleus, which then emits at least one gamma ray. The prompt positron signal and delayed neutron capture form a distinct coincidence signature. The detectors are doped with gadolinium to shorten the neutron capture time and increase the energy of the gamma signal, but captures on hydrogen nuclei are also analyzed to enhance statistics.

The near and far detectors are almost identical in design, to maximize cancellation of detector-related uncertainties in a two-detector analysis. Previous Double Chooz publications describe the detector design in detail.[3]

2.2 Single-detector θ_{13} measurements

Double Chooz performed its first oscillation analysis in 2011, becoming the first reactor-based experiment to find evidence for a nonzero value of θ_{13}. Since that time, nearly four times more livetime has been analyzed and many new techniques have been employed. One novel strategy has been searches for IBD interactions followed by neutron captures on hydrogen. The Gd-doped target of the Double Chooz detector has a volume of 10 m^3, while the surrounding vessel of undoped scintillator contains more than twice that volume. Consequently, searching for H signals roughly doubles the potential signal population. Here, we report the most recent Gd- and H-based measurements from the Double Chooz far detector.

The Gd measurement is derived from 467.90 live days, which yield 17,358 IBD candidates. Relative to the previous Gd-based publication,[3] major improvements in this analysis include

[a] This approximation leaves out a θ_{12}-dependent term, which is negligible for reactor antineutrino energies and baselines less than 1 km. In addition, the mass splitting is not exactly Δm^2_{31} but a combination of Δm^2_{31} and Δm^2_{32}.

improved detection efficiency, reduced backgrounds, and a more precise energy scale. Another enhancement is the inclusion of 7.2 live days of data taken when both reactors were shut down. That data helps validate background predictions and serves as a background constraint in oscillation fits.

In this latest Gd analysis, efficiency-related uncertainties contribute a signal normalization uncertainty of 0.6%, while the dominant background, decays of cosmogenic ^{9}Li and ^{8}He, contribute about 1%. The energy scale uncertainty is approximately 0.7%. A signal normalization uncertainty of 1.7%, by far the dominant contribution, comes from reactor flux modeling.

We perform two types of fits to extract $\sin^2 2\theta_{13}$ from the data. The most precise result comes from a rate- and spectrum-shape-based fit which includes the reactor-off data as well as independent background predictions. This Rate+Shape fit yields $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$. The second type of fit, which is completely rate-based, exploits the fact that the signal rate scales with reactor power, while the background rate does not. In this fit, data is divided into periods of low reactor power (typically when a single reactor is operating), periods of high reactor power (typically when both are operating), and periods in which both reactors are off. A unique advantage of this Reactor Rate Modulation (RRM) fit is that it does not rely on *a priori* background estimates. For the latest Gd dataset, the RRM fit yields $\sin^2 2\theta_{13} = 0.060 \pm 0.039$. Figures 1 and 2 display the Rate+Shape and RRM fits, respectively. Full details of these analyses have been published.[4]

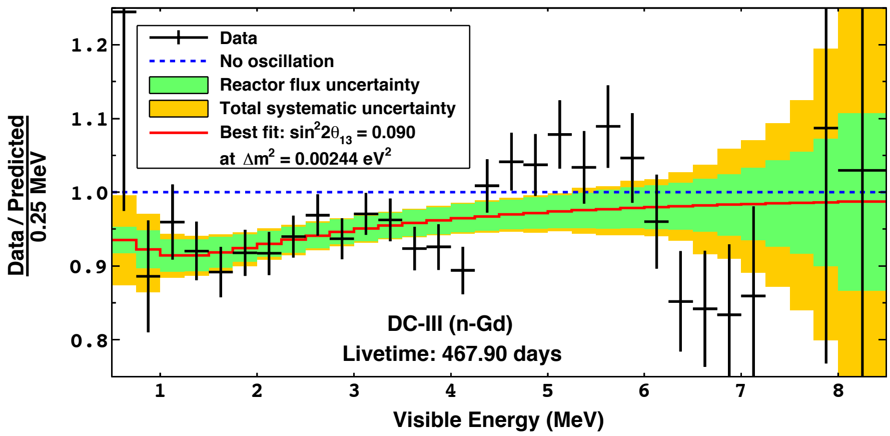

Figure 1 – The ratio of observed, background-subtracted IBD candidates to the no-oscillation prediction (black points with statistical error bars) in the latest Gd-based, Rate+Shape θ_{13} analysis. The red line shows the best fit to the data, with $\sin^2 2\theta_{13} = 0.90$. The dashed blue line shows the ratio expected in the case of no oscillation. The gold band shows the total systematic error in each bin; the green band shows reactor flux uncertainty.

3 Projections for two-detector analyses

An analysis of the H capture channel is underway for the same dataset used in the latest Gd measurement. This new analysis represents a great increase in precision over the first H-based measurement published by Double Chooz.[5] In the previous measurement, a large contamination from accidental coincidences resulted in a signal-to-background ratio of 1:1. A powerful new selection technique, based on an Artifical Neural Network, has increased that ratio by an order of magnitude. Detection efficiency and energy scale systematics have also improved significantly. The results of this analysis, the final single-detector θ_{13} measurement from Double Chooz, will be released in 2015.

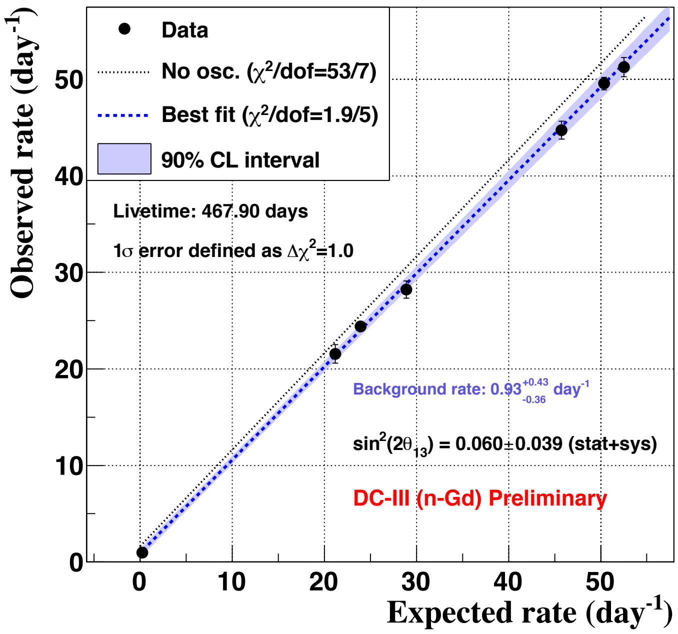

Figure 2 – The rate of observed IBD candidates, as a function of the no-oscillation prediction, for the seven reactor power bins used in the latest Gd-based Reactor Rate Modulation analysis (black points with statistical error bars). The dashed blue line shows the best fit, at $\sin^2 2\theta_{13} = 0.060$, while the gray dashed line corresponds to the no-oscillation hypothesis. The blue region is the 90% CL interval for the fit.

3.1 Additional measurements

In the last year, Double Chooz has also explored physics beyond θ_{13}. One notable result is the event-by-event identification of ortho-Positronium (o-PS) formation.[6] Ortho-Positronium is the singlet bound state of a positron and electron, with a lifetime in liquid scintillator of a few nanoseconds. In some cases, its delayed annihilation can be identified in the PMT pulse profile of positron candidates. This identification allows the collection of a pure positron sample and may have wider applications in liquid scintillator detectors.

Double Chooz also contributed to an unexpected revision in our understanding of the reactor antineutrino flux. In the latest Gd-based oscillation analysis, the spectrum of observed candidates strongly disagreed with expectations in the 4-6 MeV region. This excess is clearly visible in Figure 1. Multiple explanations were tested, including new background contributions, energy scale distortions, and efficiency effects; none of these were compatible with the data. The observation that the excess scaled with reactor power, along with similar distortions in the H-based spectrum and spectrum from the CHOOZ experiment, suggested that a flaw in reactor flux modeling could be the cause.[3] This hypothesis is also supported by observations from Daya Bay and RENO. A resolution, in terms of the underlying reactor or nuclear physics models, is now a subject of interest for researchers in those fields.

3.2 Near detector status

The Double Chooz near detector was completed in December 2014. It began taking data that month. Initial data quality checks show that the spectrum of spallation neutron captures in the near detector is very similar to that in the far detector, demonstrating the near detector's capabilities for IBD detection. The rate of single, uncorrelated events in the near detector is also similar to the far detector rate, indicating the achievement of radiopurity and shielding goals.

3.3 Two-detector θ_{13} precision

The near detector will tremendously enhance the θ_{13} precision of the Double Chooz experiment. Figure 3 shows a preliminary projection of future precision. This projection is based on a Rate+Shape fit, assuming the background levels and systematic uncertainties of the Gd-based analysis described in Section 2.2. Further improvements in precision will be possible through the addition of H capture data and continuing reduction of systematic uncertainties.

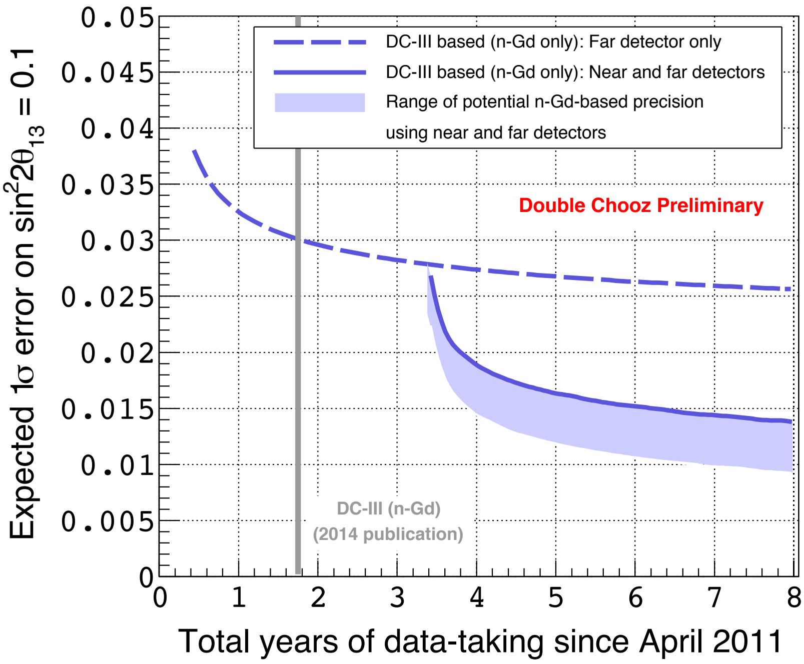

Figure 3 – A projection of the Double Chooz precision in a measurement of $\sin^2 2\theta_{13}$, using only Gd capture data and assuming the same background levels and systematic uncertainties as the latest Gd-based analysis. The vertical axis is the expected 1σ uncertainty on a measurement of $\sin^2 2\theta_{13} = 0.1$. The dashed curve reflects measurements made with only far detector data; the solid curve includes both near and far detector data. The light blue region shows possible improvements in precision which may be achieved by reduction of systematic uncertainties in a Gd-based analysis.

A unique feature of the Double Chooz near detector is its nearly isoflux location. In a perfect isoflux arrangement, the near detector would be located such that it observes precisely the same mixture of events from the two reactors as the far detector. In this case, the near detector would perfectly monitor the flux in the far detector, allowing maximal cancellation of reactor-related uncertainties. Because its site has only two reactors, compared to the six at Daya Bay and RENO, Double Chooz was able to achieve the layout closest to an isoflux geometry. This condition allows simple, model-independent suppression of over 90% of reactor-related uncertainty.

3.4 Studies of reactor flux and sterile neutrinos

The near detector provides opportunities for at least two physics measurements beyond θ_{13}. Since it will detector hundreds of IBD interactions each day, the near detector will allow a much more precise study of the reactor spectrum features introduced in Section 3.1. The combination of near and far detector data will also open sensitivity to sterile neutrino oscillations in the range of $\Delta m^2_{41} = 0.001 - 1$ eV^2. A study of sterile neutrino sensitivity is in progress. Both reactor spectrum and sterile neutrino studies will benefit from data taken when only one reactor is operating. During these periods, such as in the first several months of 2015, ambiguity about the neutrino baseline and reactor conditions is eliminated.

4 Conclusions

Double Chooz has produced a number of high-quality measurements in its single-detector phase. Now, as the experiment enters the two-detector phase, it will begin to approach its full potential in measuring θ_{13}. At the same time, near detector data will allow studies of the reactor antineutrino flux and possible sterile neutrino signals.

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