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Results from the Double Chooz experiment

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Abstract. Recent results from the Double Chooz experiment on the neutrino mixing angle θ_{13} are presented. Two detectors are located at distances of 400 m and 1050 m from the reactor cores of the Chooz nuclear power plant, to measure the original neutrino flux from the reactor cores and the disappearance of neutrinos, respectively. The Far Detector has taken data since 2011 while the Near Detector started the data taking in 2014. The latest far detector only result with gadolinium capture events is $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$. Studies using hydrogen capture events also have been improved and the combined result of gadolinium and hydrogen capture events is obtained as $\sin^2 2\theta_{13} = 0.088 \pm 0.033$.

1 Introduction

In the standard three-flavor framework, neutrino oscillations are described by the three mixing angles, three mass squared differences and a CP-violating phase. While other parameters except for CP-violating phase have been measured, the mixing angle θ_{13} remained unknown until recently and reactor experiments [1–4] have proved it as non-zero value. In the reactor neutrino experiments, a disappearance of electron antineutrino, $\bar{\nu}_e$, is observed. The survival probability of $\bar{\nu}_e$ is described as:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{1.27 \Delta m^2_{13} L}{E_{\bar{\nu}_e}} \right), \quad (1)$$

where L is a distance and $E_{\bar{\nu}_e}$ is energy of $\bar{\nu}_e$. The mass squared difference of Δm^2_{13} is measured by the MINOS experiment as $\Delta m^2_{13} = 2.44^{+0.90}_{-0.10}$ [5]. The reactor neutrino has energy of O(MeV), and the first maximum oscillation point is about 1 km.

$\bar{\nu}_e$ is detected by using the inverse β-decay (IBD) process: $\bar{\nu}_e + p \to e^+ + n$. The positron annihilates with an electron and observed as the prompt signal with an energy deposit related to the incoming neutrino energy as: $E \simeq E_\nu - 0.8$MeV. The neutron is captured on either Gd or H and observed as the delayed signal. Gd capture occurs after a mean time of 30 μs and emits 8 MeV signal, while H capture occurs after a mean time of 200 μs and emits 2.2 MeV signal. A background is strongly suppressed by the coincidence of these prompt and delayed signals.

2 The Double Chooz experiment

The Double Chooz experiment has two detectors in the Chooz nuclear power plant in France, which has two reactor cores producing 4.25 GW_{th} each. The Near Detector (ND) and the Far Detector (FD) are located at ∼ 400 m and ∼ 1050 m from the cores, respectively.

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These two detectors were made based on the identical design. The detector consists of the Inner Detector (ID), the Inner Veto (IV) and the Outer Veto (OV). The innermost of the ID is the neutrino target (NT) filled with 10 m^3 Gd-loaded liquid scintillator. The NT is surrounded by a 55 cm thick Gd-free liquid scintillator, called γ-catcher (GC), to capture γ-rays escaping from the ND. The outside of the GC is the Buffer region filled with mineral oil and the 390 photomultiplier tubes (PMTs) placed there. The IV is a 50 cm thick liquid scintillator layer with 78 PMTs, surrounding the Buffer region. A stainless steel vessel separates the IV and the Buffer region. The OV is the detector of plastic scintillator strips covering the top of the Double Chooz detector, to identify cosmic muon background events.

Three types of backgrounds are accounted for the analysis: cosmogenetic isotopes, such as ^{9}Li, emitting a neutron with their β decay; correlated signals due to proton recoil from spallation fast neutrons and stopping muons producing a Michel-electron; and accidental background. All these events are estimated from the data and subtracted from the final IBD candidates.

The FD has worked since 2011 while the ND started to take data in 2014 and all results on θ_{13} in this presentation used only the FD data.

3 Gadolinium Analysis Result

The neutrino candidates are selected from samples from which events within 1 ms after a muon event and light noise events are rejected. The prompt and the delayed candidates are selected with energy of 0.5MeV $< E_{\text{prompt}} <$ 20MeV and 4MeV $< E_{\text{delayed}} <$ 10MeV, respectively. The coincidence selection is applied by using differences of timings (ΔT) and the positions (ΔR) of the prompt and the delayed signals as: 0.5μs $< \Delta T <$ 150μs and $\Delta R <$ 100cm. To select isolated events, the prompt events that have other events within 200 μs before and 600 μs after are rejected. For the data that has the OV information, no OV hit is required. The veto using the IV information is deployed to suppress fast neutron and accidental events. For stopping muon events, the vertex reconstruction goodness method (F_v veto) is used. Cosmogenetic events are rejected by ^{9}Li likelihood method. The details of the selection can be found in [1].

The data of 460.67 live days is used and 17351 IBD candidates are selected. Two different analysis methods are attempted for the oscillation analysis: reactor rate modulation analysis and rate + shape analysis.

For the reactor rate modulation (RRM) analysis, the data is divided into different reactor configurations: two reactor cores on, one of the reactor cores is off, and both reactor cores are off. By comparing observed and expected IBD event rates at different configurations, θ_{13} and the background rate is simultaneously extracted from the linear correlation between the observed and the expected events.

Figure 1 shows the correlation of the expected and observed event rates with the best-fit prediction in the left, and the contour plot of allowed region on (θ_{13}, B) plane in the right. The best fit result of the RRM is $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$.

The rate + shape analysis uses the prompt energy spectrum. The data is divided into 40 energy bins and compared to Monte Carlo simulation. The shape of cosmogenetic background is estimated from ^{9}Li vetoed events. The correlated background is assumed to be flat with energy and extrapolated from the higher energy region. The accidental background is estimated from the off-time window events.

Figure 2 shows the prompt energy spectrum and the ratio of the data to the non-oscillation prediction. The best fit value is $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$.

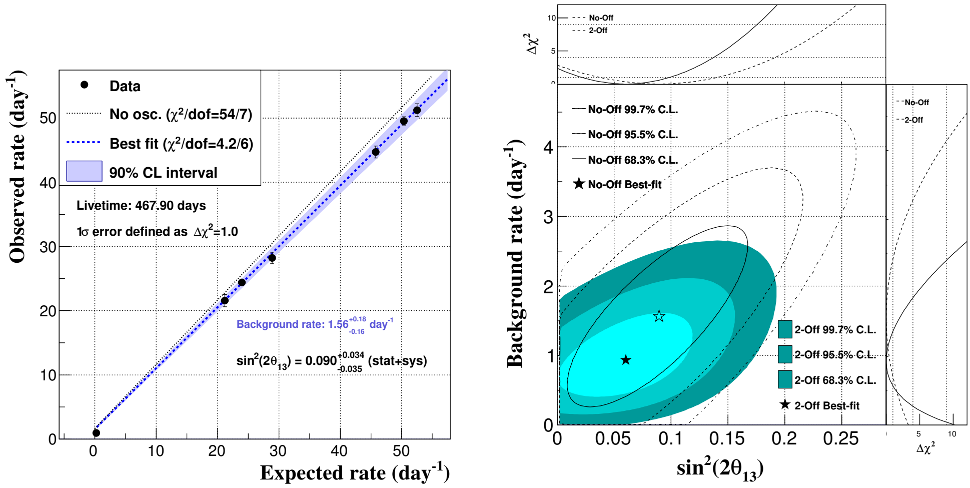

Figure 1. RRM fit including the reactor-off data for Gd analysis. The left plot shows (θ_{13}, B) fit, superimposed to the null oscillation hypothesis assuming the background estimates. The right plot shows 68.3, 95.5 and 99.7 % C.L. allowed regions on (θ_{13}, B) plane.

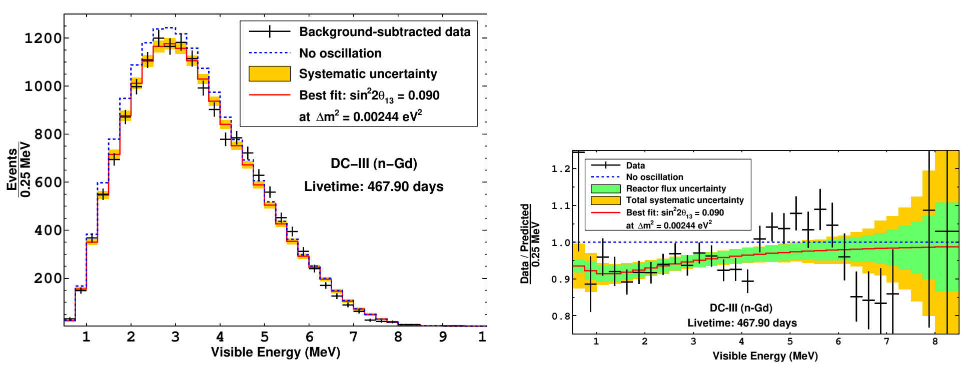

Figure 2. Prompt energy spectrum of IBD candidate of Gd analysis. In the left plot, black points shows data, blue dashed line shows the prediction of non-oscillation prediction, and red line shows the best fit. Background components of accidental, cosmogenetic (^{9}Li + ^{8}He) and fast neutron and stopping muons are also shown. The right plot shows the ratio of the data to the non-oscillation prediction.

4 Hydrogen Analysis Result

H events have more statistics than Gd events, while more accidental background events appear because the delayed energy is lower and ΔT of prompt and delayed events is longer.

The basic event selections are similar with the Gd analysis. The prompt and the delayed candidates are selected with energy of 1.0MeV $< E_{\text{prompt}} <$ 20MeV and 1.3MeV $< E_{\text{delayed}} <$ 3MeV, respectively. The correlation selections are 0.5μs $< \Delta T <$ 800μs and $\Delta R <$ 120cm. For isolation cut, no event is required 800 μs before and 900 μs after prompt signal. OV-veto, IV-veto and F_v veto are also applied as Gd analysis.

To improve the background rejection, an artificial neutral network (ANN) method has been developed with three parameters of delayed energy, ΔR and ΔT. ANN method reduces $\sim$ 95 % of backgrounds compared to previous cut-based analysis [6].

In addition, flash-ADC information for each PMT is used for multiplicity pulse shape (MPS) veto. In the fast neutron events, additional prompt recoils can happen and it makes additional pulses. Rejecting events with such an additional pulses results 25 % reduction of the fast neutron events.

Further details of H analysis are described in [2].

For the H analysis, the data of 452.72 live days is used and 31835 IBD candidates are selected. The best fit value is $\sin^2 2\theta_{13} = 0.095^{+0.038}_{-0.039}$ for the RRM analysis, and $\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$ for the rate + shape analysis.

The combined result of Gd and H events is also obtained for the RRM analysis. Figure 3 shows the correlation plot and the counter plot for Gd and H combined analysis.

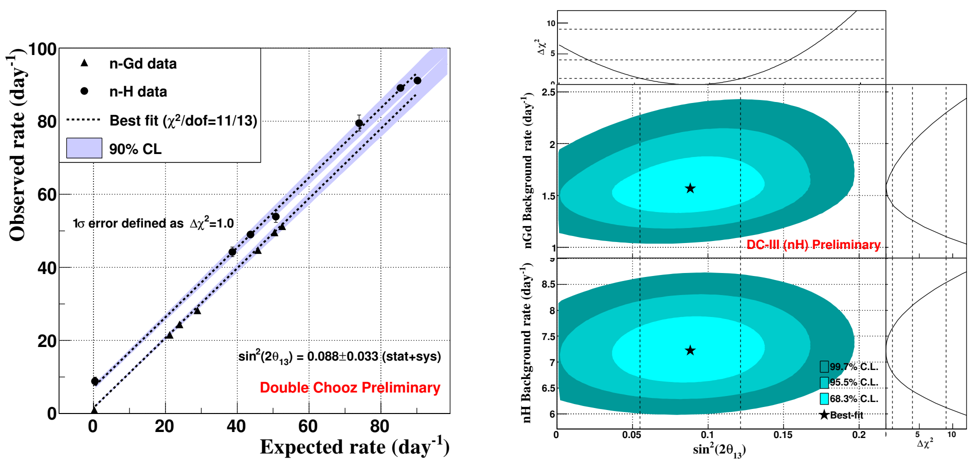

Figure 3. Gd and H combined RRM RRM fit including the reactor-off data. The left plot shows (θ_{13}, B) fit, superimposed to the null oscillation hypothesis assuming the background estimates. The right plot shows 68.3, 95.5 and 99.7 % C.L. allowed regions on (θ_{13}, B) plane.

The best value is obtained as $\sin^2 2\theta_{13} = 0.088 \pm 0.030$.

5 Spectrum distortion

A spectrum distortion is found above 4 MeV of the prompt energy as shown in Figure 2. There is an excess around 5 MeV in observed IBD rate, while it was confirmed as insignificant effect on θ_{13} results because the statistics and the oscillation effect are much more in the lower energy region. And a strong correlation with the reactor power is reported in [1].

6 Conclusion

Double Chooz published θ_{13} measurement results for Gd and H analysis. In each analysis, the RRM analysis and the rate + shape analysis are attempted to obtain θ_{13} value. Gd analysis shows

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$\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$ and $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$ for the RRM analysis and the rate + shape analysis, respectively. Gd and H combined result is obtained as $\sin^2 2\theta_{13} = 0.088 \pm 0.030$.

The ND data taking started in 2014. The current large uncertainty on the neutrino flux will be reduced by the FD data and the uncertainty on $\sin^2 2\theta_{13}$ will be reduced as 10 % level in a few years.

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