Background-independent measurement of $\theta_{13}$ in Double Chooz

Double Chooz Collaboration

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1. Introduction

Recently, three reactor neutrino experiments, Double Chooz [1], Daya Bay [2] and RENO [3] have successfully determined the leptonic mixing angle $\theta_{13}$ to be clearly non-zero. These disappearance experiments are sensitive to the oscillation amplitude and have measured $\sin^2(2\theta_{13})$ to be $\sim 0.1$. They identify reactor antineutrinos via the inverse beta decay (IBD) reaction $\nu_e p \to e^+ n$ and use a coincidence between the prompt positron and the delayed neutron capture signals in order to separate antineutrinos from background.

Of the three experiments, Double Chooz is the only one to be exposed to only two reactors. The total antineutrino flux therefore changes significantly during reactor maintenance periods when one of the two reactor cores is not functioning. At certain times both cores at Chooz were turned off simultaneously, providing the unique opportunity to determine the background in a model-independent way. In this paper we present an analysis of the Double Chooz data in which the background rate and the oscillation amplitude are determined simultaneously by analyzing the Chooz data in which the background rate and the oscillation amplitude are determined simultaneously by analyzing the data with two time periods, thus being the same in all the considered reactor periods. We restrict our analysis to rate measurements only. In order to identify antineutrino events via the inverse beta decay, we use both neutron captures on Gd and on H. Finally, we present a combined Gd- and H-analysis and compare our final result with the published ones that rely on the energy spectrum information. This analysis is also useful as a direct test of the background model used for the Double Chooz oscillation analysis. We will show that our background determination is in full agreement with the prediction derived from our background model.

2. Reactor Rate Modulation analysis

In order to measure the mixing angle $\theta_{13}$ by means of reactor neutrino experiments, the observed rate of $\bar{\nu}_e$ candidates ($R_{\text{obs}}$) is compared with the expected one ($R_{\text{exp}}$). As Double Chooz data have been taken for different reactor thermal power ($P_{th}$) conditions, this comparison can be done for different expected averaged rates, in a Reactor Rate Modulation (RRM) analysis. In particular, there are three well-defined reactor configurations: (1) the two reactors are on (2-On data), (2) one of the reactors is off (1-Off reactor data), and (3) both reactors are off (2-Off reactor data). For the 1-Off and 2-Off reactor data, the expected antineutrino rate takes into account the residual neutrinos ($R^{\text{res}}$) generated after the reactors are turned off as $\beta$ decays keep taking place. While the antineutrino flux generated during reactor operation is computed as described in [1], the rate of residual antineutrinos is estimated as described in [4].

From the comparison between $R_{\text{exp}}$ and $R_{\text{obs}}$ at different reactor powers both the value of $\theta_{13}$ and the total background rate $B$ can be derived. The correlation of the expected and observed rates follows a linear model parametrized by $\sin^2(2\theta_{13})$ and $B$:  
$$ R_{\text{obs}} = B + R_{\text{exp}} = B + (1 - \sin^2(2\theta_{13}) \eta_{\text{osc}}) R^{\text{res}}, $$

where $R^{\text{res}}$ is the expected rate of actual antineutrinos in absence of oscillation and $\eta_{\text{osc}}$ is the average disappearance coefficient.
(\sin^2(\Delta m^2 L/4E)). This coefficient is computed by means of simulations for each one of the data points as the integration of the normalized antineutrino energy \( (E) \) spectrum multiplied by the oscillation effect driven by \( \Delta m^2 \) (taken from [5]) and the distance \( L \) between the reactor cores and the detector. The average \( \eta_{\text{osc}} \) value corresponding to the full data sample is computed to be 0.55. Fitting the data to the above model provides a direct measurement of the mixing angle and the total background rate. In previous Double Chooz publications [1,6], the rates and the energy spectra of the three dominant background sources (fast neutrinos, stopping muons and cosmogenic isotope \( \beta-n \) decays) were estimated from reactor-on data, therefore building a background model that was fitted along with the mixing angle. In contrast, the RRM analysis extracts the total background rate from data in a model-independent and inclusive way, where all background sources (even possible unknown ones) are accounted for. The accuracy and precision on the fitted value of \( \sin^2(\Delta m^2 L/4E) \) is the distance between the detector and reactor \( i \). The error bars in the expected rates (not visible for all data points) account for the systematic errors.

### 3. Systematic uncertainties

There are three sources of systematics to be accounted for in the RRM analysis: (1) detection efficiency \( \sigma_\text{det} \), (2) residual \( \nu_e \) prediction in reactor-off data \( \sigma_\nu_e \), and (3) \( \nu_e \) prediction in reactor-on data \( \sigma_\nu_r \). The detection efficiency systematics in n-Gd (n-H) \( \nu_e \) sample are listed in [1] (see also [6]), from which the total uncertainty \( \sigma_\text{det} \) is derived to be 1.01% (1.57%). The uncertainty in the rate of residual antineutrinos has been computed with core evolution simulations as described in [4] for the 1-Off and 2-Off reactor periods: a \( \sigma_\nu_r = 30\% \) error is assigned to \( R^{\nu_r} \). Finally, a dedicated study has been performed in order to estimate \( \sigma_\nu_r \) as a function of the thermal power.

To a good approximation, all sources of reactor-related systematics are independent of \( P_{\text{th}} \), with the exception of the uncertainty on \( P_{\text{th}} \) itself, \( \sigma_P \). This fractional error is 0.5% [1] when the reactors are running at full power, but it increases as \( P_{\text{th}} \) decreases. In [1,6], \( \sigma_P \) is assumed to be 0.5% for all data. This is a very good approximation when one integrates all the data taking samples, and consequently all reactor operation conditions, as more than 90% of the data are taken at full reactor power. However, this is not a valid approximation in the current analysis as it relies on separating the data according to different reactor powers. In order to compute \( \sigma_P \) for different \( P_{\text{th}} \), an empirical model is fitted to a sample of measurements provided by EdF (the company operating the Chooz nuclear plant). An effective absolute uncertainty of about 35 MW is derived from the fit, being the dominant component of the model. This absolute error translates into a \( 1/P_{\text{th}} \) dependence of the relative power uncertainty, which is used to compute the errors in \( R^{\nu_r} \). The resulting errors (both from \( P_{\text{th}} \) only and from all reactor systematic sources listed in [1]) are shown in Fig. 2, for the case of the n-Gd \( \nu_e \) expectation. The total error \( \sigma_i^T \) (where \( i \) stands for each data point) ranges from 1.75% (reactors operating at full power) to 1.92% (one or two reactors not at full power). In a conservative approach, the \( \sigma_i^T \) errors are assumed to be fully correlated.
4. Background independent oscillation results

The $R_{\text{obs}}$ fit is based on a standard $\chi^2$ minimization. Without taking into account the 2-Off data, the $\chi^2$ definition is divided into two different terms: $\chi^2 = \chi^2_{\text{on}} + \chi^2_{\text{pull}}$, where $\chi^2_{\text{on}}$ stands for 2-On and 1-Off reactor data and $\chi^2_{\text{pull}}$ accounts for the systematic uncertainties. Assuming Gaussian-distributed errors for the data points involving at least one reactor on, $\chi^2_{\text{on}}$ is built as follows:

$$\chi^2_{\text{on}} = \sum_{i=1}^{N} \frac{(R_{i} - R_{i}^\text{exp}[1 + \alpha^d + \alpha^e + \sigma_\text{on} + \alpha^\nu] - B)^2}{\sigma^2_{\text{stat}}(\text{on})},$$

where $N$ stands for the number of bins (6, as shown in Fig. 1), and where $\alpha^d$, $\alpha^e$ and $\alpha^\nu$ stand for pulls associated with the detection, reactor-on and residual antineutrino systematics, respectively. The weights $k_i$ are defined as $1/(\alpha + \sigma_\text{on})$, where $\sigma_\text{on} = 1.75\%$ stands for the error when the cores operate at full power. The fraction of residual antineutrinos, $\sigma_\text{on}$, in each data point is defined as $w_i = R_{i}^\text{exp}/R_{i}^\text{on}$. The term $\chi^2_{\text{pull}}$ incorporates the penalty terms corresponding to $\alpha^d$, $\alpha^e$ and $\sigma_\text{on}$:

$$\chi^2_{\text{pull}} = \left(\frac{\alpha^d}{\sigma_\text{on}}\right)^2 + \left(\frac{\alpha^e}{\sigma_\text{on}}\right)^2 + \left(\frac{\alpha^\nu}{\sigma_\text{on}}\right)^2.$$

According to this $\chi^2$ definition, a fit to the two free parameters $\sin^2(2\theta_{13})$ and the total background rate $B_{\text{Gd}}$ is performed with the n-Gd $\bar{\nu}_e$ candidates sample. The results are shown in Fig. 3 with best-fit point (empty star) and C.L. intervals. The best fit values are $\sin^2(2\theta_{13}) = 0.21 \pm 0.12$ and $B_{\text{Gd}} = 2.8 \pm 2.0$ events/day, where the errors correspond to $\Delta \chi^2 = 2.3$. Although the precision is poor, these results are consistent within $1\sigma$ with the ones presented in [1]. In particular, the best fit value for the background is consistent with the independent estimate in [1] ($1.9 \pm 0.6$ events/day) and with the direct measurement obtained from the 2-Off data in [4]: $B_{\text{2Off}} = 0.7 \pm 0.4$ events/day (once accidental background is subtracted).

In order to improve the RRM determination of $\sin^2(2\theta_{13})$, the 2-Off data can be incorporated into the fit as an additional data point for $P_{\text{on}} = 0$ MW. The $\chi^2$ is built then as $\chi^2 = \chi^2_{\text{on}} + \chi^2_{\text{off}} + \chi^2_{\text{pull}}$. Due to the low n-Gd statistics in the 2-Off reactor period, the corresponding error in $R_{\text{obs}}$ is considered to be Poisson-distributed. As a consequence, $\chi^2_{\text{off}}$ is defined as a binned Poisson likelihood following a $\chi^2$ distribution:

$$\chi^2_{\text{off}} = 2 \left( \frac{N_{\text{obs}} \ln \frac{N_{\text{obs}}}{B + N_{\text{exp}}[1 + \alpha^d + \alpha^e]} + B + N_{\text{exp}}[1 + \alpha^d + \alpha^e] - N_{\text{obs}}} \right).$$

where $N_{\text{obs}} = N_{\text{obs}}^\text{Gd}$, $T_{\text{off}}$ and $N_{\text{exp}} = N_{\text{exp}}^\text{Gd} - T_{\text{off}}$; $T_{\text{off}}$ is the live time of the 2-Off data sample. The results of the $\sin^2(2\theta_{13})$ fit including the 2-Off data are presented in Fig. 3 with solid best-fit point and C.L. intervals. The best fit values are $\sin^2(2\theta_{13}) = 0.107 \pm 0.074$ and $B_{\text{Gd}} = 0.9 \pm 0.6$ events/day.

As the 2-Off data provide the most precise determination of the total background rate in a model-independent way, the introduction of this sample (or equivalently the value of $B_{\text{2Off}}$) in the RRM fit provides a direct constraint to $B$. Therefore, hereafter we consider $\theta_{13}$ to be the only free parameter in the fit, while $B$ is treated as a nuisance parameter. Therefore, the best fit error on $\theta_{13}$ corresponds to $\Delta \chi^2 = 1$. The outcome of the corresponding fit using the n-Gd sample can be seen in Fig. 4. The best fit value of $\sin^2(2\theta_{13})$ is now $0.109 \pm 0.049$, with a $\chi^2$/dof of 4.2/5. The value of $\theta_{13}$ is in good agreement with the result of [1] ($\sin^2(2\theta_{13}) = 0.109 \pm 0.039$), while the error is slightly larger due to the fact that the RRM analysis does not incorporate energy spectrum information. The RRM fit does not change the measurement of the total background rate provided by the 2-Off data significantly, as the best fit estimate of $B_{\text{Gd}}$ is $0.9 \pm 0.4$ events/day.

While the best fit value of the total background rate depends on the antineutrino candidate selection cuts, the best fit of $\theta_{13}$ must be independent of these cuts. In order to cross-check the above results, the RRM analysis has also performed for a different set of selection cuts; those applied in the first Double Chooz oscillation analysis [7]. This selection does not make use of the muon outer veto (OV) and does not apply a showering muon veto. Therefore, the number of correlated background events in the $\bar{\nu}_e$ candidates sample is increased (according to the estimates, by 1.3 events/day). In this case, the input value for the background rate provided by the 2-Off data is $B_{\text{2Off}} = 2.4 \pm 0.6$ events/day [4]. The fit yields $\sin^2(2\theta_{13}) = 0.120 \pm 0.053$, which is fully consistent.
with the above results, while the background rate is not signifi-
cantly modified either in this case ($B_{\text{Gd}} = 2.6 \pm 0.6$ events/day).

As shown in [6], the precision of the oscillation analysis based
on n-H captures is not as good as the n-Gd one due to the
larger systematic uncertainties and the larger accidental
contamination. This applies also to the RRM analysis. The n-H fit yields
$\sin^2(2\theta_{13}) = 0.091 \pm 0.078$ ($\chi^2$/dof = 10.8 ± 3.4 events/day, $B_{\text{H}} = 8.7 \pm 2.5$ events/day) with $\chi^2$/dof = 4.8/5, consistent with the results in [6] ($\sin^2(2\theta_{13}) = 0.097 \pm 0.048$). The n-H candidates can be fitted together with the n-Gd ones in order to increase the pre-
cision of the analysis and to test the consistency of both selections.

In order to perform a global fit, a combined $\chi^2$ is built from the
sum of the Gd and H ones:

$$\chi^2 = \chi^2_{\text{Gd}} + \chi^2_{\text{H}} + \chi^2_{\text{pull}}.$$  

(5)

While $\sigma_r$ and $\sigma_\nu$ are fully correlated between the n-Gd and
n-H candidates samples (they do not depend on selection cuts, but
on reactor parameters), there is a partial correlation ($\rho$) in
the detection efficiency uncertainty, which has been estimated to be
at the level of 9%. This overall factor comes from correlated
and anti-correlated contributions. The correlated contributions are
due to the spill-in/out events (IBD events in which the prompt and the
delayed signal do not occur in the same detection volume, as
defined in [1]) and the number of protons in the detection vol-
umes. The anti-correlated contribution is due to the uncertainty
in the fraction of neutron captures in Gd and H. From this
value, one can decompose $\sigma_d$ into uncorrelated ($\sigma^d_{\text{Gd-H}} = 0.91$ and
$\sigma^d_{\text{H-H}} = 1.43$%) and correlated contributions ($\sigma^c = 0.38$%) for the
n-Gd and n-H data. The pull $\sigma^d$ in Eq. (3) is now divided into three
terms accounting for the correlated and uncorrelated parts of the
detection error: $\sigma^d_{\text{Gd-H}}, \sigma^d_{\text{H-H}}$ and $\sigma^c$. Accordingly, $\chi^2_{\text{pull}}$ is defined as:

$$\chi^2_{\text{pull}} = \left(\frac{\alpha^d_{\text{Gd-H}}}{\sigma^d_{\text{Gd-H}}}\right)^2 + \left(\frac{\alpha^d_{\text{H-H}}}{\sigma^d_{\text{H-H}}}\right)^2 + \left(\frac{\alpha^c}{\sigma^c}\right)^2 + \left(\frac{\alpha^\nu}{\sigma^\nu}\right)^2.$$  

(6)

The combined Gd-H RRM fit is shown in Fig. 5. The best fit value of the mixing angle is $\sin^2(2\theta_{13}) = 0.102 \pm 0.028$ (stat.) ±
0.033(sys.), for $\chi^2$/dof = 8.0/11. This value is consistent within
1$\sigma$ with respect to the single n-Gd and n-H results, while the pre-
cision is slightly improved. The relative error on $\sin^2(2\theta_{13})$ goes
from 46% to 42%. As in the previous results, the output values of the
total background rates are consistent with the input values:
$B_{\text{Gd}} = 0.9 \pm 0.4$ events/day and $B_{\text{H}} = 9.0 \pm 1.5$ events/day. The
impact of the correlated part in $\sigma^d$ has been proven to be negligible
by performing a fit assuming no correlation.

5. Comparison of Double Chooz $\theta_{13}$ results

Including this novel RRM analysis, Double Chooz has released
four different $\theta_{13}$ analysis results. These results are obtained as follows: (1) with n-Gd candidates in [1], (2) with n-H candidates
in [6], [3] with n-Gd candidates and the RRM analysis, and (4) with
n-H candidates and the RRM analysis. Beyond the common detec-
tion and reactor-related systematics, these four analyses rely on
two different candidate samples (n-H and n-Gd), and two different
analysis techniques (rate + shape fit with background inputs and
RRM). The four $\sin^2(2\theta_{13})$ values obtained are presented in Fig. 6,
as well as the combined Gd-H RRM result. All the values are consis-
tent within 1$\sigma$ with respect to the most precise result, which is
provided by the rate + shape fit.
further improved by combining the n-Gd and n-H $\tilde{\nu}_e$ samples: $\sin^2(2\theta_{13}) = 0.102 \pm 0.028^{\text{(stat.)}} \pm 0.033^{\text{(syst.)}}$. The outcome of the RRM fit is consistent within 1$\sigma$ with the already published results for $\theta_{13}$, yielding a competitive precision. Beyond the cross-check of the background estimates in the Double Chooz oscillation analyses, the RRM analysis provides, for the first time, a background model independent determination of the $\theta_{13}$ mixing angle.

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