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The Double Chooz experiment

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The Double Chooz reactor neutrino experiment is measuring the neutrino mixing angle θ_{13}. This parameter is determined via the observation of a electron antineutrino flux deficit at a distance of about 1 km from the two Chooz reactors in France. The neutrinos are detected by a coincidence signal of a prompt positron and a delayed neutron, both produced inside the liquid scintillator detector by a neutrino interaction on hydrogen. The combined result of two analyses, one focusing on neutron captures on gadolinium and one studying neutron capture events on hydrogen, is presented. We find $\sin^2(2\Theta)_{13} = 0.109 \pm 0.035$. The result is confirmed by an analysis which compares the observed and expected neutrino rates as a function of reactor power. This rate analysis, which does not require any background model, since it uses a direct background measurement from data with both Chooz reactors off is in agreement with the rate + shape result.

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1. Introduction

In the three neutrino paradigm, the neutrino flavor eigenstates are related to the mass eigenstates through the PMNS mixing matrix, which can be parameterized by three mixing angles and a CP violating phase. Two of the three mixing angles were already known to be large from several solar, atmospheric and reactor neutrino experiments [1], whereas for the third one, θ_{13}, there were just upper limits for many years [2]. After first hints of non-zero values of the third mixing angle θ_{13} from global neutrino data analysis [3], Double Chooz provided for the first time such an indication from a single reactor neutrino experiment [4]. This result was then confirmed with higher precision by similar reactor experiments as Daya Bay [5] or RENO [6]. The final value delivered from all reactors is likely to remain our best knowledge for a long time and will be used for high precision neutrino oscillations studies such as the measurement of the leptonic CP violation.

Nuclear reactors are a strong and pure source of electronantineutrinos. In Double Chooz our far detector is located 1050 m from two 4.25 GW$_{th}$ reactors of the EDF Chooz nuclear power plant. The laboratory has an overburden of 300 mw.e. which acts as a shielding against cosmic rays. The Double Chooz concept will be completed after the installation of the near detector which will be at a distance of 415 m with a rock shielding of 115 mw.e. Its purpose is to reduce the systematic uncertainty of the experiment by measuring the reactor antineutrino flux with negligible oscillation effect. Reactor experiments at distances close to the first oscillation minimum at $1-2$ km from the reactor cores provide a clean measurement of θ_{13} without significant parameter correlations and with no matter effects. The Double Chooz experiment profits from its rather simple reactor configuration with two reactors close to each other and two detectors almost on the iso-flux line.

The energy and time dependent expected number of antineutrino events in our detector, N_{nu}^{exp} can be calculated by

$$N_{nu}^{exp} = \frac{\varepsilon N_H}{4\pi L^2} \cdot \frac{P_{th}(t)}{< E_f >} \cdot < \sigma_f > . \tag{1.1}$$

Here the first factor contains the detector related parameters like the number of target protons N_H, the detection efficiency ε and the distance to the reactor L. The thermal power P_{th} of each reactor core is provided by EDF company as a fraction of the total power and evaluated every minute. At the nominal full power of 4250 MW the uncertainty on P_{th} is 0.5 %. To calculate the mean energy released per fission $< E_f >$ the fractional fission rates of each istope in the reactor core needs to be known. To accurately model the evolution of these fractional fission rates two complementary simulation codes, MURE and DRAGON, are used. The normalization of the spectrum averaged mean cross section $< \sigma_f >$ is anchored to the Bugey4 rate measurement at 15 m reactor distance, which has an uncertainty of 1.4 %. Therefore, the rather large uncertainties in the reference spectra [7] are reduced in the far detector only phase of Double Chooz. The difference in fuel composition between Bugey4 and Double Chooz reactor cores is corrected. In $< \sigma_f >$ is also included the cross section of the neutrino detection reaction which is the inverse beta decay on hydrogen atoms (H) in the liquid scintillator $\bar{\nu}_e + p \rightarrow n + e^+$ (E$_{threshold}$ = 1.8 MeV). The delayed coincidence signal of the prompt positron event ($1-9$ MeV) and the delayed neutron capture on gadolinium (Gd) releasing 8 MeV energy with a capture time of about 30μs provide effective background reduction. Due to the low background environment in Double Chooz, we are also able to analyse the neutrino rate from neutron captures on H (E= 2.2 MeV, capture time around 200μs).

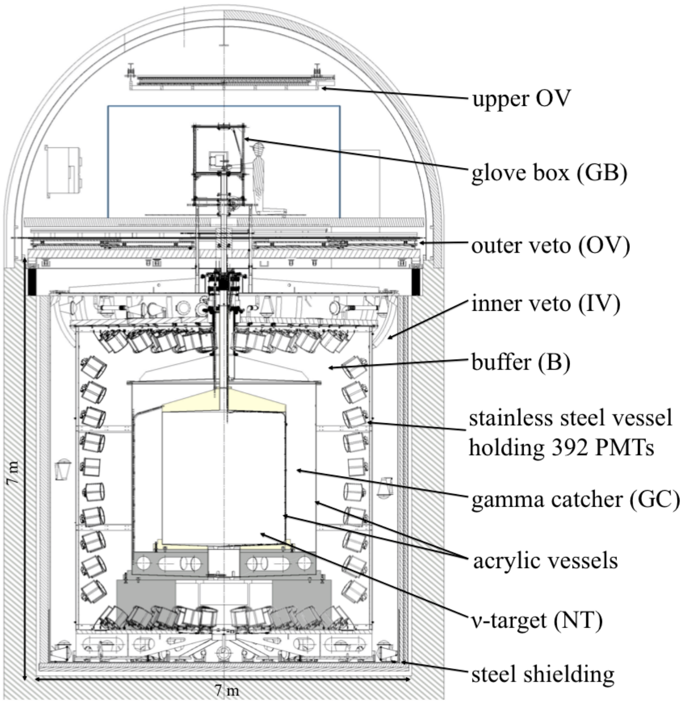

Figure 1: A cross-sectional view of the Double Chooz detector system.

2. The Double Chooz detector

Figure 1 shows the design of the Double Chooz detector. In the center are 8.3 tons of Gd loaded liquid scintillator (Gd-LS) [8] embedded in an 8 mm thick transparent acrylic vessel. Around this target vessel is the Gamma Catcher scintillator (GC) with a total mass of 18.1 tons contained in a 12 mm acrylic vessel. Its main purpose is to convert the full energy of the gamma radiation produced in a neutrino interaction into scintillation light. The third volume in the detector is a non-scintillating buffer liquid with a total mass of about 80 tons. It reduces accidental background events created by natural radioactivity coming from outside. The buffer volume is optically separated from the outer detector components by a 3 mm thick cylindrical steel vessel. On the inside of this steel vessel 390 photomultiplier tubes (PMT) are installed [9, 10]. Muons and its spallation products are one of the main sources for background. They are detected in the liquid scintillator of the Inner Veto, which is around the buffer volume. An additional Outer Veto system consisting of several sheets of plastic scintillators is installed on top of the detector.

Calibration sources can be inserted from a glove box on top of the detector along the central axis of the target vessel with mm precision. Gamma sources as ^{137}Cs, ^{68}Ge and ^{60}Co are used to calibrate the energy scale and monitor detector stability. The detector response to neutrons and efficiencies are studied with a ^{252}Cf source. These sources can also be deployed inside the GC using a motor-driven wire guided by a steel tube. A LED fiber system injects light into the detector from fixed points. This data is used to measure PMT and electronics gains as well as time offsets. Furthermore, cosmic rays and spallation neutrons are analyzed for calibration purposes.

3. Energy reconstruction

The deposited visible energy E_{vis} of the prompt event in the neutrino detection reaction is directly related to the neutrino energy E_{nu} by $E_{vis} = E_{\nu} - 0.8$ MeV. There are three corrections applied to get the energy scale of our detector taking into account gain nonlinearities, inhomogeneities and time variations of the detector response. The neutron capture peak on H (2.223 MeV) from spallation interactions is used to characterize the response nonuniformity over the full volume of the scintillators. Spallation neutrons are also used to correct and monitor the time variations of the detector response. After one year of data taking with the Double Chooz far detector there is no evidence for any instability of the Gd-LS which was a limiting factor in the Chooz experiment [2]. The absolute energy scale is calibrated using neutron captures on H from a deployed Cf source at the center of the target vessel. After calibration, discrepancies in response between MC simulations and data are used to estimate a systematic uncertainty in the energy scale of 1.13 %.

4. Neutrino selection

In Double Chooz neutrino events are selected for neutron captures on Gd and H. The Gd analysis [11] takes advantage of the high energy delayed event well above the region of natural radioactivity and the short coincidence time. Those features provide a large signal to background ratio (S/B). In the H analysis [12] there is an independent statistical sample with different background and efficiency systematics. Since the H sample also includes the GC region as target the fiducial volume is almost a factor three larger compared to the Gd case.

There are several common selection cuts in the Gd and H analysis. First it is required that the light signal arrives uniform in space and simultaneous in time at the PMT. In this way background caused by instrumental light production, e.g. from the PMT bases is strongly reduced. To reduce cosmogenic backgrounds triggers within a 1 ms window following a tagged muon and prompt events with a coincident signal in the OV are rejected. The prompt energy window is $0.7 - 12.2$ MeV in both analyses.

Different selection cuts are required for the delayed energy cut and the coincidence time window (Δt). The delayed energy window is $6 - 12$ MeV for Gd selection and $1.5 - 3$ MeV for H captures. The Gd Δt cut is $2 - 100\mu$s and $10 - 600\mu$s for H. To reduce accidental coincidences which are much higher in the H analysis due to the lower delayed energy window a spatial cut is applied in the H selection. The prompt and delayed event must not be separated by more than 0.9 m. In an extra cut candidates within a 0.5 s window after a high energy muon ($E > 600$ MeV) crossing the inner detector are rejected in the Gd analysis to reduce correlated background events. With this additional cut the total veto time increases to 9.2 %. Finally no extra trigger event around the coincidene signal is allowed in both selections.

With these selection cuts 8249 (36284) neutrino candidate events are observed in 227.9 (240.1) days of live time in the Gd (H) analysis. The S/B is around 17 (1) in the Gd (H) analysis.

5. Backgrounds

The background in Double Chooz can be divided into three classes. The first one are random coincidences (accidentals). This type of background can be measured with rather high precision by applying the selection cuts described above, but shifting the coincidence time window by 1 s to avoid correlations. The second type of backgrounds are correlated signals of fast neutrons (FN) or stopping muons (SM). For the FN, which are typically produced by muons missing the detector, the neutrino signal is mimicked by recoil protons from neutron scattering (prompt) followed by a neutron capture in the fiducial volume after thermalization (delayed). The SM arise from muons stopping and decaying in the detector without being tagged by the veto systems. Here the muon track mimics the prompt event and the decay Michel electron the delayed. Whereas the accidentals are the dominating source of background in the H analysis most of the background in the Gd analysis is due to the third class of background events coming from products of spallation processes on ^{12}C induced by cosmic muons. In this case βn emitters like ^{9}Li or ^{8}He mimic the full signature of neutrino candidates. Since the half life of these isotopes is more than 100 ms it is not possible to veto all of them without significant dead-time. This cosmogenic isotopes background has the highest uncertainty of all backgrounds in both analyses. The background related rate uncertainty is about 1.6 % (1.7 %) in the Gd (H) analysis which is comparable to the error associated with the reactor flux prediction [11, 12].

One of the unique features in the Double Chooz analysis compared to other reactor neutrino experiments is the possibility of measuring the background with both reactors off [13]. In an analysis of about 7 days of reactor off-off time 1.0 ± 0.4 background events per day were measured in the Gd analysis (residual reactor antineutrinos subtracted). This is consistent with the expected 2.0 ± 0.6 events per day as estimated from the background modeling during reactor on data. Since the measured rate in the off-off data is below the estimate from the background model we are confident that our background modeling is complete and no additional background source of significant relevance was overseen. Consistent results were also found in the H analysis. The accidentals subtracted measured background of 11.3 ± 3.4 events per day is in reasonable agreement with the estimated 5.8 ± 1.3 events per day.

6. Rate and shape analysis

The neutrino data with neutron captures on Gd and H, which are statistically independent, were analysed separately with the selections and livetime described above. The oscillation analysis is based on a fit to antineutrino rate and spectral shape. Data are compared to a reactor power based antineutrino Monte Carlo sample. In the Gd (H) oscillation analysis the data are separated into 18 (31) variably sized bins between 0.7 and 12.2 MeV. A prediction of the observed number of signal and background events is constructed for each energy bin. Systematic and statistical uncertainties are propagated to the fit by the use of a covariance matrix in order to properly account for correlations between energy bins. By the use of the energy spectrum in the analysis information on background rates can be gained from the fit, in particular between 8 and 12 MeV, where the number of predicted neutrino events is very small. The fit parameters for correlated backgrounds due to FN/SM and cosmogenic isotopes are allowed to vary as part of the fit, and they scale the rates of the two backgrounds. The energy scale is also allowed to vary linearly constrained by its uncertainty of 1.13 %. For the mass splitting Δm^2_{31} the value from the MINOS measurement of $2.32 \pm 0.12 \cdot 10{-}3$ eV^2 [14] was used. Consistent Θ_{13} results were found for the rate and shape

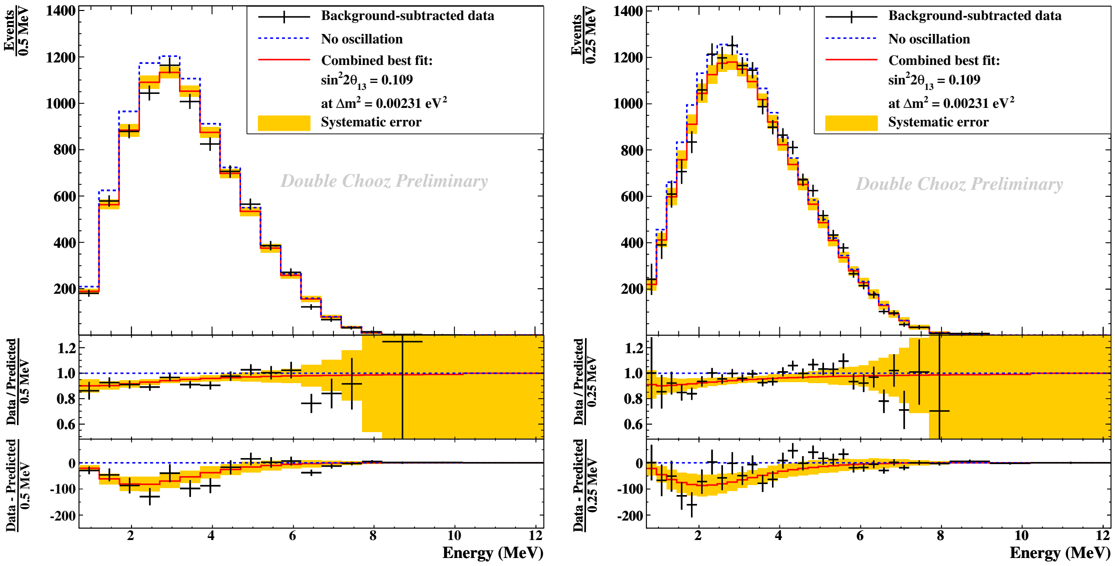

Figure 2: Background subtracted prompt energy spectra for Gd and H analysis and combined best fit result (red line). The black data points are shown with statistical errors. The dashed blue line shows the prediction without neutrino oscillation. Gold bands indicate systematic errors.

analyses for neutron captures on Gd and H as well as for analyses using only the rate information. [11, 12].

Figure 2 shows the background subtracted prompt spectra for both data sets. A combined fit to the spectra enlarges the signal sample and partially cancels systematic errors. Correlations between the systematic uncertainties in the Gd and H analysis were estimated and taken into account. Other than in the individual analyses, the reactor off-off measurement is added to the combined fit as a constraint on the correlated and cosmogenic backgrounds. The combined fit result for $\sin^2(2\Theta_{13})$ is 0.109 ± 0.035.

7. Reactor rate modulation analysis

In Double Chooz, the mixing angle Θ_{13} is also determined in a special rate only analysis. Here the observed and expected (in absence of oscillation) neutrino candidate rates are compared for different reactor power conditions. In the "standard" configuration both reactors are on, but there is also a lot of data with one reactor off. Sometimes the reactors are not running at full power and for about 7 days even both reactors were off. If the observed candidate rate is plotted versus the expected rate for the different reactor power conditions, the data points can be fitted to a linear model parametrized by Θ_{13}. The advantage of this approach is that no a priori assumptions on the background need to be made. The fit is constrained by the direct background measurement during the period with both reactors off. Therefore, this analysis is independent of background models. This reactor rate modulation analysis was done individually for neutron captures on Gd and H and a combined fit for both data samples was performed. The results obtained in this analysis are in very good agreement with our combined rate and shape result. This proves the robustness of our antineutrino analyses.

8. Conclusions

The international Double Chooz neutrino oscillation experiment was the first new generation reactor experiment suggesting a positive observation of Θ_{13}. Double Chooz measured this neutrino oscillation parameter via two independent techniques and two different disjoint samples of reactor neutrino interactions in the detector based on whether the neutron captures in Gd or H. The third neutrino mixing angle is determined in a rate + shape and a reactor rate modulation analysis. The remarkable agreement of 4 measurements, each having different systematics, demonstrates the robustness of the results and the high precision background knowledge.

To gain on precision the H and Gd measurements have been combined, considering all correlated terms. For the combined fit in the rate + shape analysis we obtain $\sin^2(2\Theta_{13}) = 0.109 \pm 0.035$. In the current far detector only phase the sensitivity is limited by the dominant antineutrino flux uncertainties. Once the near detector is used, Double Chooz is expected to reach 10 % precision on the $\sin^2(2\Theta_{13})$ result.

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