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Double Chooz and recent results

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Summary. — The reactor $\bar{\nu}_e$ disappearance experiment Double Chooz, located in France near the power plant of Chooz, has as main goal the measurement of the θ_{13} mixing angle. For the first time, in 2011, the experimental results gave an indication for a non-zero value of such an oscillation parameter. The mixing angle was successively measured using only the far detector finding the best fit value of $\sin^2(2\theta_{13}) = 0.090^{+0.033}_{-0.029}$. The near detector started data taking in December 2014 and it will allow to reduce the systematic errors so far dominated by the reactor flux uncertainty. In this paper a review of the experiment is presented focusing on the so-called Gadolinium-III results (Double Chooz Collaboration (Abe Y. *et al.*), *JHEP*, **10** (2014) 086; **02** (2015) 074). Furthermore additional physics measurements are presented such as the capability of Double Chooz to identify the ortho-positronium state on event by event basis.

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PACS `36.10.Dr` – Positronium.

1. – Introduction

The discovery of a non-zero value of the θ_{13} mixing angle is an important breakthrough in neutrino oscillation physics, which opened the way for the CP violation search in the leptonic sector. We are now entering the precision era on θ_{13} measurements were reactor antineutrino experiments such as Double Chooz [1], DayaBay [2] and RENO [3] and long baseline experiments such as T2K [4] will combine their measurements to reduce the uncertainties and constrain as much as possible the possible region in the $\sin^2(2\theta_{13})$–δ_{CP} phase space plane.

In this picture Double Chooz had a major role giving for the first time indication of a non-zero value of the θ_{13} mixing angle [5], using for the first time the neutron capture on Hydrogen for an independent measurement [6], performing a reactor rate modulation analysis [7] which allows to cross check our knowledge on the background, and observing for the first time the so called "5 MeV excess" [8].

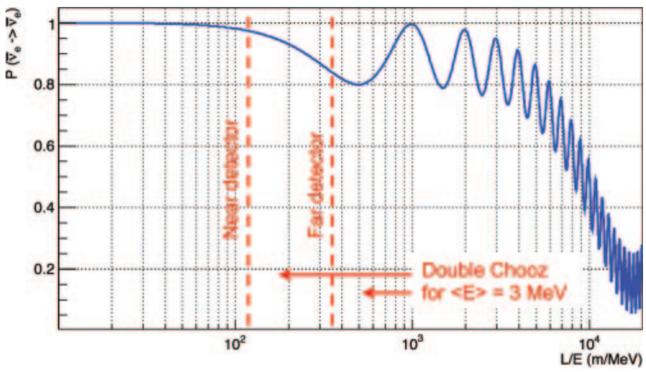

Fig. 1. – Oscillation probability $P(\bar{\nu}_e \to \bar{\nu}_e)$ as a function of L/E. The regions covered by the near and the far detector are shown by the red dashed lines.

2. – Neutrino detection and detector design

Double Chooz is a reactor neutrino oscillation experiment that aims at the observation of the $\bar{\nu}_e \to \bar{\nu}_e$ transition. The probability for such an oscillation can be calculated using the approximated formula given in eq. (1) where L is the baseline, E the neutrino energy, θ_{13} the mixing angle that we want to measure, and Δm^2_{23} the mass splitting between the mass eigenstate 2 and 3:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right). \tag{1}$$

The idea of the experiment is to measure the large flux of neutrinos coming from the two reactor cores (the isotropic generation amounts to about $10^{21} \nu_e$ per second) with two identical detectors. The first detector is located at about 400 m from the reactor cores (where the oscillation probability is very small) whereas the second one is hosted in the former Chooz experiment laboratory at about 1 km from the reactors, at about the first maximum of oscillation as can be seen in fig. 1.

The ratio of the spectra measured at the far and near site gives a direct measurement of the mixing angle θ_{13}. This evaluation using two identical detectors allows for a cancellation of many systematic errors related mostly to the flux normalization and detector efficiency evaluation.

Neutrinos are detected via the Inverse Beta Decay (IBD) process (*i.e.* $\bar{\nu}_e + p \to e^+ + n$) which has an energy threshold of 1.8 MeV. The neutrino energy spectrum is a convolution of the reactor flux and the IBD cross section, resulting in a mean energy of about 4 MeV in a range of 2 to 8 MeV. The neutrino energy (E_ν) and the visible energy released by the positron (E_p) in the detector are related according to eq. (2), whereas T_n is the kinetically energy of the emitted neutron:

$$E_p = E_\nu - T_n - 0.8\,\text{MeV}. \tag{2}$$

The signal signature is given by a two-fold coincidence (space and time correlation) between the prompt signal given by the positron ionization and annihilation, and the delayed signal given by the γ's emitted in the neutron capture on Gd (~ 8 MeV with a

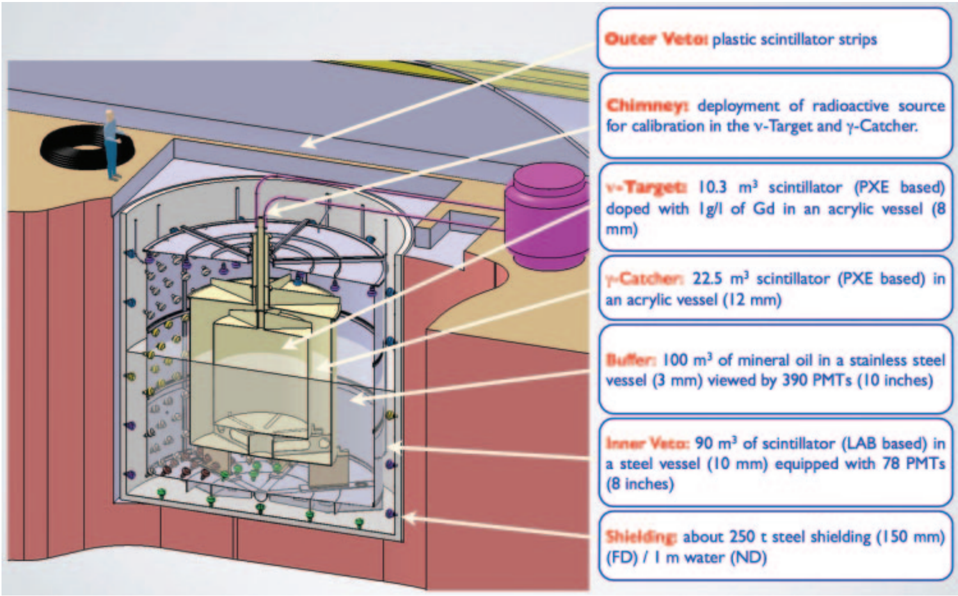

Fig. 2. – Double Chooz detector design.

mean delayed Δt of $\sim 30\,\mu$s with respect to the prompt signal) or H (2.2 MeV with a mean delayed Δt of $\sim 200\,\mu$s with respect to the prompt signal).

The detectors are made up of several sub-detector layers, each one with a specific task, as it can be seen in fig. 2 and detailed descriptions of all the components can be found in ref. [1].

3. – Background

The background can be divided into two categories: accidental and correlated.

In the accidental background, the prompt signal is typically radioactivity from the materials, in particular from PMTs, or from the surrounding rock. The delayed signal is given by a fast neutron, produced by cosmic muons spallation in the rock surrounding, which enters the detector, and gets thermalized and absorbed on Gd (or H) within the allowed time window from the prompt signal.

Correlated background can be given by three different processes: fast neutrons, stopping muons or cosmogenic.

Fast neutrons from cosmic muons could undergo nuclear interactions in the detector and produce recoil protons (*i.e.* the prompt signal) before being thermalized and captured.

Stopping muons could enter the detector from the chimney and stop there, making the Inner Veto useless and giving a small signal which could fake a prompt positron one. The Michel electron coming from the muon decays has a large energy spectrum which include also the energy window selected for the neutron capture and can therefore fake a delayed signal.

Finally correlated background is due to long-lived $\beta - n$ isotopes such as ^{9}Li or ^{8}He. They are cosmogenic isotopes produced by muons in the detector for which a veto is not possible given the long lifetime of the order of hundreds of milliseconds.

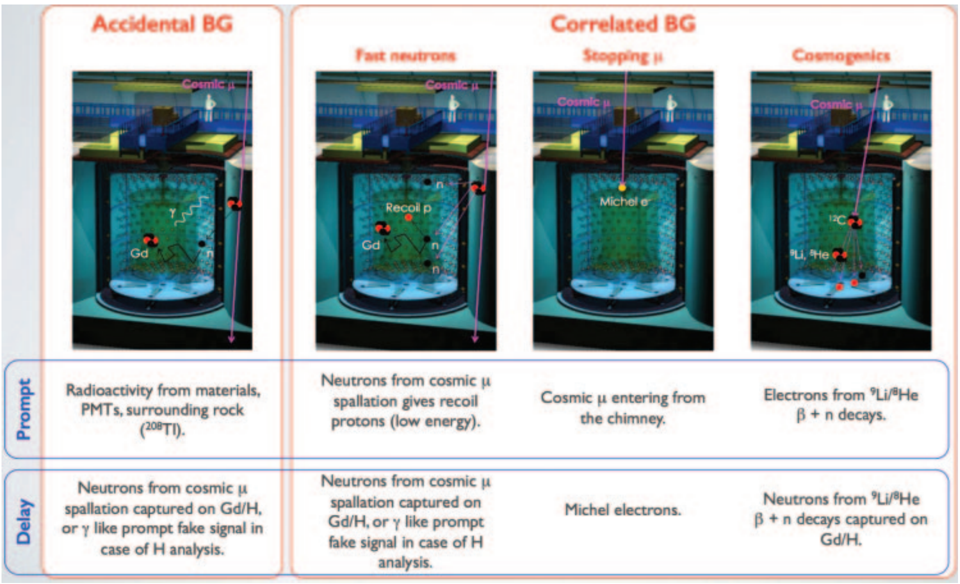

Fig. 3. – Cartoon showing the different prompt and delayed signals for accidental and correlated backgrounds.

A summary of the different background with a cartoon showing the different prompt and delayed signal can be seen in fig. 3.

Full details on the different background estimates can be found in ref. [8]. The cosmogenic background was computed using rate and shape information and it accounts for $0.97^{+0.41}_{-0.16}$ events per day.

The fast neutrons and stopping muon shape was estimated using the Inner Veto and their rates were computed looking at the 20–30 MeV energy region and extrapolated in the region of interest for IBD candidates (0.5–20 MeV). They account for 0.604 ± 0.051 events per day.

Finally the accidental background was evaluated using off-time coincidence windows after the IBD signal and the result is 0.070 ± 0.003 events per day.

4. – Results

With respect to previous publication, the so called "Gadolinium-III" publication [8] has an increase of a factor two in statistics counting 17358 neutrino candidates for a live time of 467.9 days.

The neutrino candidate rate as a function of the live time can be seen in fig. 4. The total uncertainty on $\sin^2(2\theta_{13})$ is reduced by about 20% (from 2.7% to $+2.3\%/-2.0\%$) still dominated by the reactor flux, as mentioned in the previous section, at the level of 1.7%.

A unique feature of Double Chooz is the possibility to profit from both reactor off data (so far 7.24 days) in order to better constrain and understand the background.

The rate plus shape analysis, which now includes the reactor off data as an extra bin, yielded a value of the mixing angle of $\sin^2(2\theta_{13}) = 0.090^{+0.033}_{-0.029}$ (see fig. 5).

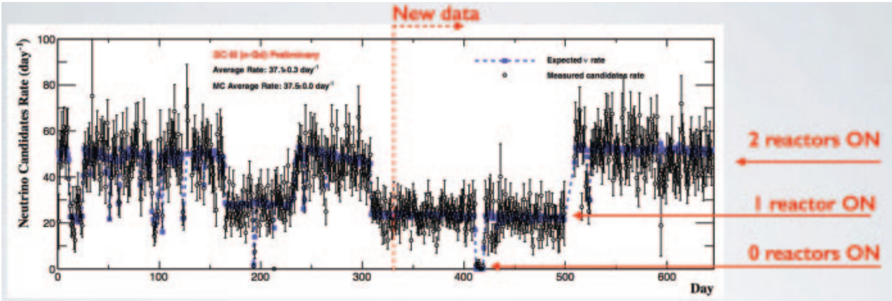

Fig. 4. – Neutrino candidates rate per day as a function of the detector live time.

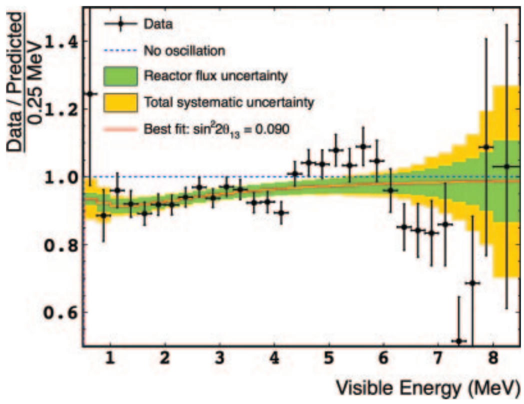

Fig. 5. – Data/predicted spectrum. The best fit is shown in red whereas in dashed blue it is shown the expectation in case of no oscillation, *i.e.* $\theta_{13} = 0$.

The independent Reactor Rate Modulation (RRM) analysis [7], which can estimate the value of the mixing angle θ_{13} with no constraint on the background, found $\sin^2(2\theta_{13}) = 0.060 \pm 0.039$, in agreement with the rate plus shape analysis. If the knowledge on the background is included in the RRM as a pull term in the fit, the result is $\sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}$ and the background estimate is $1.56^{+0.18}_{-0.16}$ events per day, in agreement with the expected $1.64^{+0.41}_{-0.17}$ events per day.

To briefly mention the so called "5 MeV excess" which is the excess of events at about 5 MeV which can be seen in fig. 5, we can say that, although not fully understood, the strong correlation with the reactor power and the results on the background estimate from the RRM point towards an unaccounted component of the reactor flux and disfavors the possibility of an unaccounted background component.

Tests were made adding an artificial excess and the changes in θ_{13} were below 10% of the uncertainty showing that the results on the mixing angle evaluation are indeed robust with respect to this unaccounted flux component.

5. – Near detector

The near detector is identical to the far one and it is located at about 400 m from the reactor cores, measuring therefore the neutrino flux before the oscillation. Its major

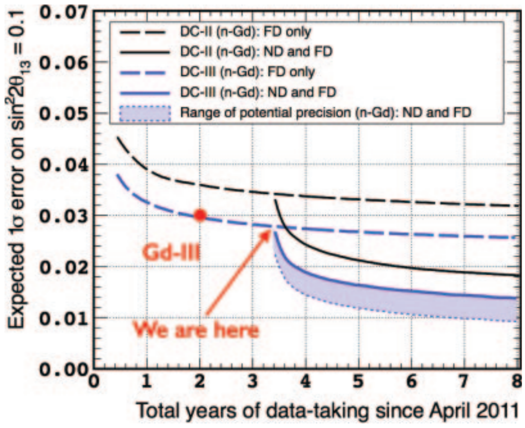

Fig. 6. – Expected error on $\sin^2(2\theta_{13})$ as a function of the years of data taking.

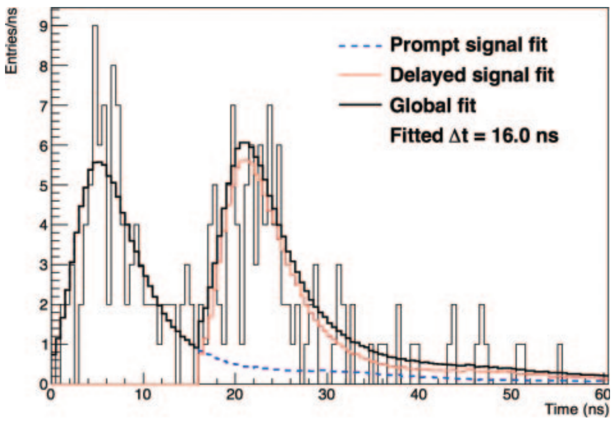

Fig. 7. – Pulse shape of an o-Ps event. The first bump represents the positron ionization whereas the second one is due to the o-Ps decay.

contribution will be indeed the reduction of the systematic uncertainty related to the flux normalization which is the dominant component when evaluating the mixing angle θ_{13} using only the far detector.

The near detector started data taking in December 2014 and the projected sensitivity shows an error on $\sin^2(2\theta_{13})$ of 0.015 in three years of data taking (see fig. 6).

6. – Additional physics

Besides the search of θ_{13} Double Chooz has performed additional physics measurements namely: Lorentz violation searches [9], sterile neutrino search (paper in preparation), neutrino directionality studies (paper in preparation) and ortho-positronium (o-Ps) observation [10].

In particular, the o-Ps observation could be exploited for a e^+/e^- separation which is interesting for background rejection in electron antineutrino physics when looking at sources such as core-collapse supernovae, geo-neutrinos or reactor monitoring [11].

The positron light emission (pulse shape) is distorted by the delay between ionization and annihilation according to the o-Ps lifetime. Such a pulse shape distortion can be used to discriminate indeed between positrons and electrons. The pulse shapes of single events can be fitted with reference ones (from calibration sources) to estimate the o-Ps lifetime as it can be seen from the event in fig. 7 where an o-Ps lifetime of 16 ns is measured.

The global Δt distribution can be fitted to estimate o-Ps fraction and lifetime: an o-Ps formation fraction of $44\% \pm 5\%$ (stat.) $\pm 12\%$ (sys.) and a lifetime of $3.68\,\mathrm{ns} \pm 0.15\,\mathrm{ns}$ (stat.) $\pm 0.17\,\mathrm{ns}$ (sys.) were measured, in agreement with the values measured with a dedicated PALS (Positron Annihilation Lifetime Spectroscopy) setup [12].

7. – Conclusions

In this paper I presented the Double Chooz experiment, aiming at the observation of the $\bar{\nu}_e \rightarrow \bar{\nu}_e$ transition to measure the θ_{13} mixing angle. The far detector is taking data since 2011 and the near detector was fully commissioned at the end of 2014. The results obtained with the far detector only were presented and results with the two detector are expected soon.

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REFERENCES

[1] Ardellier F. *et al.*, arXiv:hep-ex/0405032.
[2] DAYA-BAY Collaboration (An F. P. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 171803.
[3] RENO Collaboration (Ahn J. K. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 191802.
[4] T2K Collaboration (Abe K. *et al.*), *Phys. Rev. D*, **88** (2013) 032002.
[5] Double Chooz Collaboration (Abe Y. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 131801.
[6] Double Chooz Collaboration (Abe Y. *et al.*) , *Phys. Lett. B*, **723** (2013) 66.
[7] Double Chooz Collaboration (Abe Y. *et al.*), *Phys. Lett. B*, **735** (2014) 51.
[8] Double Chooz Collaboration (Abe Y. *et al.*), *JHEP*, **10** (2014) 086; **02** (2015) 074.
[9] Double Chooz Collaboration (Abe Y. *et al.*), *Phys. Rev. D*, **86** (2012) 112009.
[10] Double Chooz Collaboration (Abe Y. *et al.*), *JHEP*, **1410** (2014) 32.
[11] Consolati G., Franco D., Jollet C., Meregaglia A., Minotti A., Perasso S. and Tonazzo A., arXiv:1504.01884 [physics.ins-det].
[12] Consolati G., Franco D., Hans S., Jollet C., Meregaglia A., Perasso S., Tonazzo A. and Yeh M., *Phys. Rev. C*, **88** (2013) 065502.