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Double Chooz and recent results

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Summary. — Double Chooz is a reactor $\bar{\nu}_e$ disappearance experiment located in France near the power plant of Chooz. The main goal of the experiment is the measurement of the θ_{13} mixing angle and in 2011 for the first time the experiment observed 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 $\sin^2(2\theta_{13}) = 0.109 \pm 0.035$. The near detector is under construction and will start data taking by the middle of 2014 allowing to reduce the systematic errors. In this paper I make a review of the experimental results, focusing in particular on independent analyses such as the measurement of the mixing angle θ_{13} relying on the neutron absorption on gadolinium and hydrogen, and on the reactor rate modulation. I also present for the first time the capability of Double Chooz to identify the ortho-positronium state on event-by-event basis, which could be an additional handle for the electron/positron discrimination in future liquid-scintillator–based detectors.

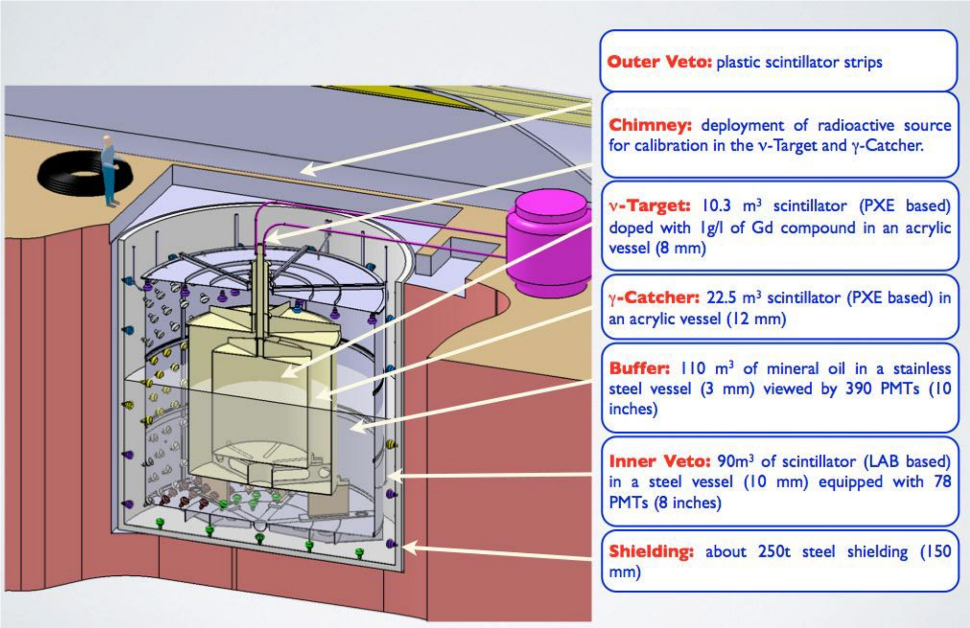
PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `36.10.Dr` – Positronium.

1. – Introduction

The recent discovery of a non-zero value of the θ_{13} mixing angle is an important breakthrough in neutrino oscillation physics. While precision measurements are still ongoing, this opened the way for the conception of future experiment aiming at the measurement of the CP violation in the leptonic sector.

Double Chooz is the first experiment who showed hints of a non-zero value of θ_{13} mixing parameter [1] and it has today a major role in the ongoing precision measurement campaign, together with DayaBay [2], RENO [3] and T2K [4].

In this paper I will present the Double Chooz experiment, the recent results, and for the first time the observation of the ortho-positronium (oPs) formation on event-by-event basis, which could be use in the future for β^+/β^- discrimination and therefore for the signal-over-noise enhancement.



Outer Veto: plastic scintillator strips

Chimney: deployment of radioactive source for calibration in the ν-Target and γ-Catcher.

ν-Target: 10.3 m^3 scintillator (PXE based) doped with 1g/l of Gd compound in an acrylic vessel (8 mm)

γ-Catcher: 22.5 m^3 scintillator (PXE based) in an acrylic vessel (12 mm)

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 inches)

Inner Veto: 90m^3 of scintillator (LAB based) in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

Shielding: about 250t steel shielding (150 mm)

Fig. 1. – Double Chooz detector design.

2. – Experimental concept and detector layout

Double Chooz is a reactor neutrino oscillation experiment that aims at the observation of the $\bar{\nu}_e$ disappearance transition. The probability of such an oscillation, as can be seen by the approximated formula in eq. (1) below has an amplitude directly proportional to the searched mixing angle θ_{13}. The other parameters related to the oscillatory behavior are the baseline L (*i.e.* the distance between the reactor and the detector), the neutrino energy E and the atmospheric mass splitting Δm^2_{23}:

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

To observe such a transition the neutrino flux is measured by the near detector at a short baseline of about 400 m (*i.e.* where the oscillation probability is basically zero) and by the far detector at a baseline of 1050 m corresponding to about the maximal probability of oscillation. A deviation of the ratio between the measured neutrino spectra at the two detectors from the expected flat one, is the signature of the non vanishing value of θ_{13}. Since the near detector will be operational by the middle of 2014 whereas the far detector started data taking in 2010, the analysis is done so far comparing the observed neutrino spectrum with the expected non–oscillated one, with the drawback of a larger systematic error on the measured mainly coming from the reactor flux uncertainty.

When the near detector will be operational, a cancellation of several systematics contributions will be possible achieving a final precision of about 10% on $\sin^2(2\theta_{13})$.

The detectors are made up of several sub-detector layers, each one with a specific task, as can be seen in fig. 1 and detailed descriptions of all the components can be found in ref. [5].

3. – Signal and background

Neutrinos are detected via the Inverse Beta Decay (IBD) process (*i.e.* $\bar{\nu}_e + p \rightarrow e^+ + n$) 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 the following 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 ($\sim 8\,\text{MeV}$ with a mean delayed Δt of $\sim 30\,\mu\text{s}$ with respect to the prompt signal) or H (2.2 MeV with a mean delayed Δt of $\sim 200\,\mu\text{s}$ with respect to the prompt signal).

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 instead be given by several processes. 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.

The last source of 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.

4. – Neutrino selection and background for θ_{13} analysis

For the neutrino selections and the measurement of the θ_{13} mixing angle, two different analysis where carried out using Gd and H as target nuclei for neutron absorption (delayed signal). If the Gadolinium analysis has the advantage of a high-energy delayed signal and therefore a strong reduction of the background, the hydrogen one has the advantage of a large statistics *i.e.* about a factor of 3 more with respect to the Gd one.

A summary of the applied cut for the neutrino selection can be found in table I. No detail is reported on the light noise cuts, which are based on the geometrical distribution of the touched PMT in the event as well as on their trigger time, which are used to reject signals coming from the spontaneous photoemission of some PMT bases (more details can be found in ref. [6]).

The number of selected neutrinos per day follows with a very good agreement the reactor power and three regions can be distinguished as can be seen in fig. 2: two reactors running, only one reactor running and both reactors off.

Table I. – *Neutrino selection cuts for* Gd *and* H *analyses.*

Cut	Gd capture	H capture
Muon veto	No triggers in 1 ms after a muon	
Outer veto	No coincidence with Outer Veto	
Light noise	See details in ref. [6]	
Energy prompt	0.7–12.2 MeV	
Energy delayed	6–12 MeV	1.5–3 MeV
Time correlation window	2–100 μs	10–600 μs
Distance correlation	-	< 0.9 m
Multiplicity	No extra events around signal	
Showering muon veto	$\Delta t_\mu > 500$ ms (after $E_\mu > 600$ MeV)	-

For both analyses the expected number of events in absence of oscillations (*i.e.* assuming θ_{13}=0), as well as the contributions of each background component, were computed (see table II).

Based on these numbers (rates) and using the spectral information (shape), it was possible to estimate the value of θ_{13} for each analysis. A combined analysis was also carried out and we obtained $\sin^2(2\theta_{13}) = 0.109 \pm 0.035$ (see table III for all the results).

An independent analysis (reactor rate modulation) [7] was developed without relying on any background model and using the unique feature of Double Chooz experiment of having a direct background measurement since we took 7.53 days data with both reactors off. The obtained result, combining neutron captures on both Gd and H, of $\sin^2(2\theta_{13}) = 0.102 \pm 0.028$ (stat.) ± 0.033 (sys.) is in good agreement with the previously obtained results.

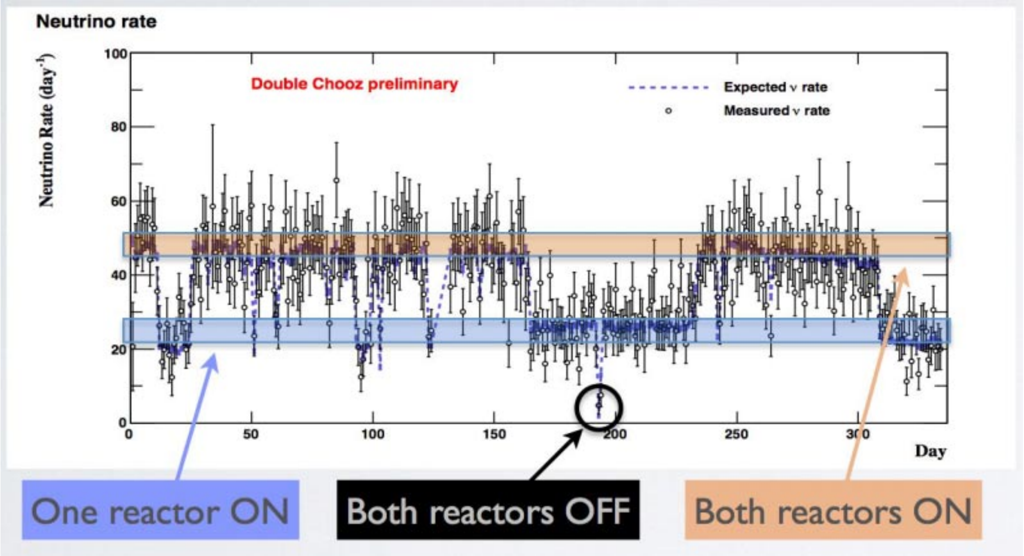


Fig. 2. – Selected number of neutrino candidates day by day.

Table II. – *Signal and background rates.*

	Gd capture	H capture
Selected neutrino candidates	8249 (228 days)	36284 (240 days)
Predicted neutrino candidates (no oscillations) + background	8936.8	36680
Accidental background	0.261 ± 0.002 ev/day	73.5 ± 0.2 ev/day
Cosmogenic background	1.25 ± 0.54 ev/day	2.8 ± 1.2 ev/day
Fast neutrons / stopping μ	0.67 ± 0.20 ev/day	2.5 ± 0.5 ev/day

Table III. – *Results on* $\sin^2(2\theta_{13})$.

Analysis	$\sin^2(2\theta_{13})$
Gd	0.109 ± 0.030 (stat.) $\pm$ 0.025 (sys.)
H	0.097 ± 0.034 (stat.) $\pm$ 0.034 (sys.)
Gd + H	0.109 ± 0.035
Reactor rate modulation	0.102 ± 0.028 (stat.) $\pm$ 0.033 (sys.)

5. – Ortho-positronium observation

A large fraction of the positrons, before undergoing annihilation, form a state of ortho-positronium (o-Ps). Its lifetime in vacuum is 142 ns, however due to the processes such as pick-off or spin-flip, in matter it is strongly reduced down to a few nanoseconds.

The formation of o-Ps introduces a temporal distortion in the pulse shape, which could in principle be used to distinguish between electrons and positrons, and therefore reduces the cosmogenic background.

The formation fraction and mean lifetime of o-Ps in Double Chooz scintillator was measured with a dedicated setup (see ref. [8] for details) and the lifetime is about 3.4 ns. Such a short lifetime induces a slight pulse shape distortion and it can be hardly used for a particle identification given the 2 ns sampling and the typical scintillating times of the same order of magnitude.

Nonetheless, we developed an algorithm that allowed for the first time to observe the o-Ps on event by event basis. The idea is to use a reference pulse shape obtained with a radioactive source, and fit the event signal with two reference pulse shapes separated by an interval Δt and normalize assuming that the second signal should correspond to the annihilation *i.e.* 1.022 MeV. The fit was applied on events with energy between 1.2 and 3 MeV since at higher energy the second signal is hidden by the first signal's tail. Some examples of the algorithm result are shown in fig. 3.

Comparing the Δt distribution obtained for the neutrino candidate selection [6] to the one obtained for a ^{60}Co run, we observed a clear excess of events at large Δt values, as it can be seen in fig. 4.

The obtained distribution can be fitted with an exponential function to extract the o-Ps formation fraction and lifetime as it can be seen in fig. 5. However, since a slight energy dependence was observed in the pulse shape, the analysis was carried out using two reference pulse shapes: one was obtained using a ^{60}Co source and the other one using a ^{137}Cs source. The o-Ps parameters where extracted taking the mean of the two analyses and the difference was included in the systematics.

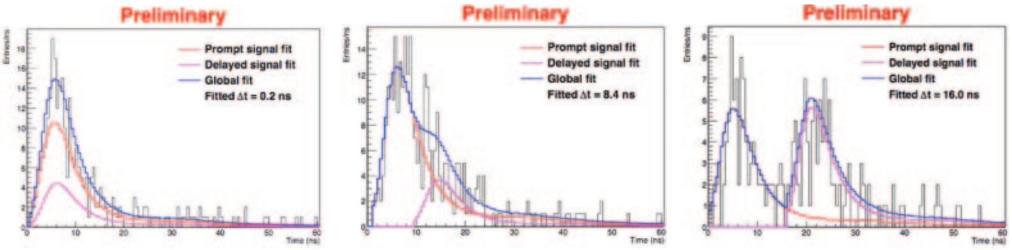


Fig. 3. – Examples of o-Ps fit. The red line represents the fit of the first signal, the pink line the fit of the second one and the blue line is the total fit of the pulse shape.

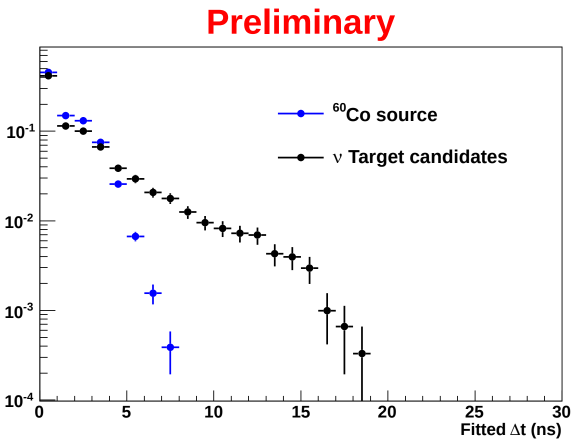


Fig. 4. – Distribution of the Δt value determined by the fit for the cobalt sample (blue), and for the neutrino candidates in the target (black), normalized to one. The neutrino candidates (DC II publication [6]) have been selected in a visible energy range between 1.2 MeV and 3 MeV.

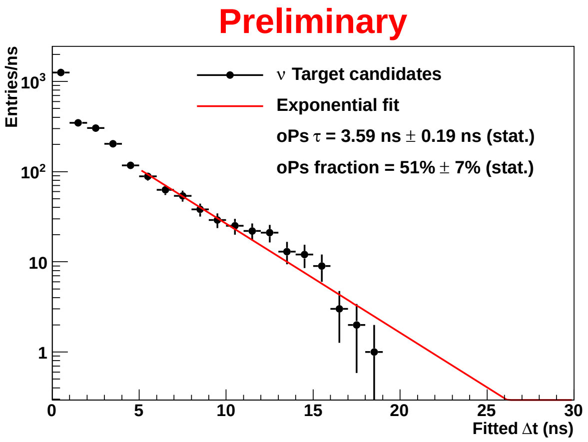


Fig. 5. – Exponential fit (red line) of the Δt value obtained for the neutrino candidates (DC II publication [6]) in the target using Co PS as reference, selected in a visible energy range between 1.2 MeV and 3 MeV. From the fit the o-Ps lifetime and fraction are computed. The statistical error is given by the fit.

Table IV. – *Results on* o-Ps *analysis.*

	o-Ps fraction (%)	o-Ps lifetime (ns)
DC measurements	42 ± 5 (stat.) ± 12 (sys.)	3.68 ± 0.15 (stat.) ± 0.17 (sys.)
NuToPs measurements	47.6 ± 1.3	3.42 ± 0.03

The obtained results are in good agreement with the expectations (measured with the NuToPs dedicated setup [8]) and it can be seen in table IV, confirming the first observation of o-Ps formation on event by event basis and paving the way for electron/positron separation in antineutrino experiments.

6. – Conclusions

Double Chooz had a major role in the discovery of a non-zero value of the θ_{13} mixing angle, and it still plays a crucial role in its precision measurement.

Double Chooz provided independent measurements on θ_{13} based on Gd and H analyses, with a combined value of $\sin^2(2\theta_{13}) = 0.109 \pm 0.035$. An independent analysis based on the reactor rate modulation, which does not assume any background parameterization but relies on its direct measurement profiting from both reactors off data, yielded consistent results: $\sin^2(2\theta_{13}) = 0.102 \pm 0.028$ (stat.) ± 0.033 (sys.).

The near detector is under construction and it will start data taking in the middle of 2014. This will result in a reduction of the systematics and the final precision on the $\sin^2(2\theta_{13})$ will be of about 10%.

Parallel analyses yielded physics results beyond the main experiment goal: background studies were carried out [9], as well as studies on the Lorentz violation [10], neutrino directionality and ortho-positronium detection on event by event basis. In particular the o-Ps analysis was presented here for the first time, and it could be an additional handle for background rejection for antineutrino detectors in particular when looking at particular sources such as a core-collapse supernovae, geo-neutrinos or for nuclear reactor monitoring.

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REFERENCES

[1] Abe Y. *et al.* [Double-Chooz Collaboration], *Phys. Rev. Lett.*, **108** (2012) 131801.
[2] An F. P. *et al.* [Daya-Bay Collaboration], *Phys. Rev. Lett.*, **108** (2012) 171803.
[3] Ahn J. K. *et al.* [Reno Collaboration], *Phys. Rev. Lett.*, **108** (2012) 191802.
[4] Abe K. *et al.* [T2K Collaboration], *Phys. Rev. D*, **88** (2013) 032002.
[5] Ardellier F. *et al.*, arXiv:hep-ex/0405032.
[6] Abe Y. *et al.* [Double Chooz Collaboration], *Phys. Rev. D*, **86** (2012) 052008.
[7] Abe Y. *et al.* [Double Chooz Collaboration], arXiv:1401.5981 [hep-ex].
[8] Consolati G., Franco D., Hans S., Jollet C., Meregaglia A., Perasso S., Tonazzo A. and Yeh M., *Phys. Rev. C*, **88** (2013) 065502.
[9] Abe Y. *et al.* [Double Chooz Collaboration], *Phys. Rev. D*, **87** (2013) 011102.
[10] Abe Y. *et al.* [Double Chooz Collaboration], *Phys. Rev. D*, **86** (2012) 112009.