12th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2011) IOP Publishing
Journal of Physics: Conference Series **375** (2012) 042064 doi:10.1088/1742-6596/375/4/042064

The Double Chooz Experiment

Patrick Pfahler on behalf of the Double Chooz Collaboration
Technische Universität München - Department for experimental astroparticle physics - James-Franck Straße 1 - 85748 Garching bei München

E-mail: patrick.pfahler@ph.tum.de

Abstract. Double Chooz is a reactor $\bar{\nu_e}$-disappearance experiment situated at the commercial nuclear power plant of Chooz in northern France. The experiment aims for the revelation of the last unknown mixing angle Θ_{13} as a part of the neutrino mixing matrix or the improvement of the upper limit for $\sin^2(2\Theta_{13})$, which is currently < 0.14 (90% CL). A newly developed gadolinium-loaded liquid scintillator as target allows the detection of electron-anti-neutrinos ($\bar{\nu_e}$) using the inverse beta decay and its distinct decay pattern ($\bar{\nu_e} + p \rightarrow e^+ + n$). Double Chooz uses two identical detectors at different distances in order to reduce systematic uncertainties. This will allow, after a data taking phase of 4 years, an improvement on $\sin^2(2\Theta_{13})$ down to < 0.03 (90% CL). The first (far) detector has successfully been installed and filled, and takes data since April of 2011. A preliminary analysis of first 120 days revealed about 4000 Neutrino-candidates and a stable detector-setup with low backgrounds. The commissioning of the second (near) detector is expected for the beginning of 2013 and will provide maximum sensitivity for the experiment.

1. Introduction

In the current view a neutrino flavor-eigenstate ($\alpha = e, \mu, \tau$) can be described as a superposition of mass-eigenstates (i = 1, 2, 3): $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$. The entanglement between these eigenstates is described by the mixing- or PMNS-matrix $U_{\alpha i}$[1]. Most of the oscillation parameters have successfully been probed in the past resulting in the measurement of the mixing angles of the atmospheric and solar sector to be $\Theta_{23} = 45°$ for $\Delta m^2_{23} = 2.32 \times 10^{-3}\, eV^2$ [1] and $\Theta_{12} = 34°$ for $\Delta m^2_{12} = 7.6 \times 10^{-5}\, eV^2$ with 90% CL[2]. The attempted measurement of the last mixing angle by the CHOOZ-Experiment solely allowed to determine an upper limit on $\Theta_{13} < 11°$ for $\Delta m^2_{13} = 2.0 \times 10^{-3}\, eV^2$ with 90% CL [3]. The interfering part of the parametrized PMNS-Matrix connecting atmospheric and solar sector includes not only the last unknown mixing angle Θ_{13}, but also a CP-violating δ-phase. The revelation of a non-zero value for Θ_{13} would allow next generation experiments to search for CP-Violation in the leptonic sector, and in consequence, to investigate e.g. the matter-antimatter-asymmetry in the universe.

2. Reactor Neutrinos

Each fission of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu leads to the production of two instable and n-rich fission isotopes, which successively decay into stable isotopes via multiple β^- decays associated with an average emission of ≈ 200 MeV and six $\bar{\nu_e}$ with energies between 0-10 MeV. Using the thermal power output of a nuclear power plant, which is in the dimension of GW's, the expected $\bar{\nu_e}$-flux is $2 \times 10^{20} \bar{\nu_e}$/s isotropically distributed on 4π.

[1] PMNS(Pontecorvo-Maki-Nakagawa-Sakata)

Journal of Physics: Conference Series **375** (2012) 042064 doi:10.1088/1742-6596/375/4/042064

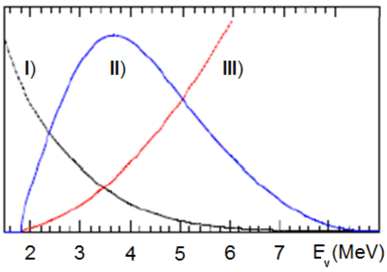


Figure 1: I) Energy spectrum for reactor-anti-neutrinos, II) Observable energy spectrum for the IBD in liquid scintillator detectors, III) Energy dependent cross-section for the inverse beta decay

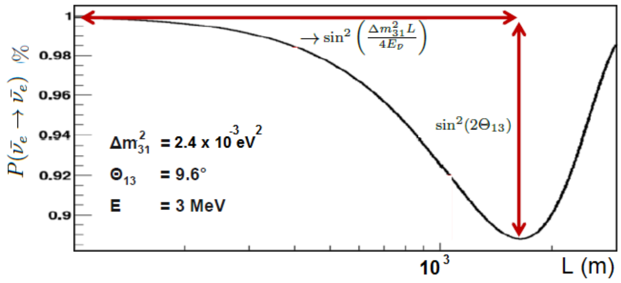


Figure 2: Survival probability using equation (1) for 3 MeV $\bar{\nu}_e$'s with $\Delta m^2_{13} = 2.4 \times 10^{-3}\, eV^2$ and $\sin^2(2\Theta_{13}) = 0.11$. The red arrows indicate the dependence of oscillation length and amplitude on variations of the free parameters in $\sin^2(2\Theta_{13})$ or $\sin^2\left(\frac{\Delta m^2_{31} L}{4E_{\bar{\nu}}}\right)$.

3. Detection principle

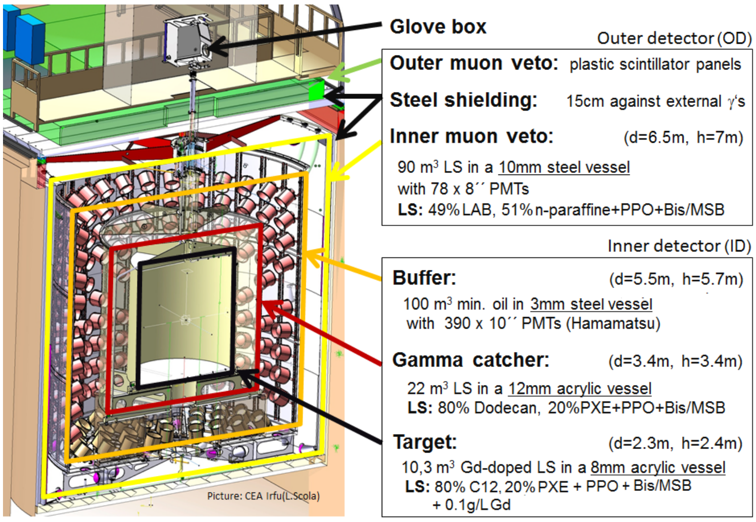
A newly developed gadolinium-loaded scintillator as target liquid allows the detection of $\bar{\nu}_e$'s using the distinct decay pattern of the inverse beta decay (IBD: $\bar{\nu}_e + p \to e^+ + n$, $Q_{thr} = 1.8\,\mathrm{MeV}$). The prompt annihilation of the positron and the delayed n-capture ($\tau_{Gd} = 30\mu s$, $E_{\gamma' s} \approx 8\,\mathrm{MeV}$) on Gadolinium provides a characteristic coincident signal used to identify IBD and to discriminate between signal and background events. The prompt annihilation of the free positron together with the energy relation between visible and initial neutrino energy ($E_{vis} \approx E_{\bar{\nu}} - Q_{thr} + 2m_e$) allows to perform neutrino spectroscopy above an energy threshold of 1.8 MeV. Figure 1 indicates two energy spectra: The black curve I) displays the energy spectrum of $\bar{\nu}_e$'s emitted by a nuclear power core, the red curve III) indicates the cross-section of the inverse beta decay (IBD), whereas the convolution of both is indicated in blue II) showing the observable energy spectrum. The survival probability for reactor-$\bar{\nu}_e$'s for small values of L/E is well approximated by:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\Theta_{13})\sin^2\left(1.27 \times \frac{\Delta m^2_{31}[eV^2] \times L[m]}{E_{\bar{\nu}_e}[MeV]}\right) \quad (1)$$

Eq (1) is shown in Figure 2 visualizing the survival probability and its dependence on L for ($E_{\bar{\nu}} = 3\,\mathrm{MeV}$, $\Delta m^2_{31} = 2.4 \times 10^{-3}\, eV^2$, and $\sin^2(2\Theta_{13}) = 0.11$). Reactor experiments like Double Chooz search for the disappearance of $\bar{\nu}_e$'s by measuring at two different locations searching for a reduced $\bar{\nu}$-rate and spectral-distortion of $E_{\bar{\nu}}$ at the farther location. Obtaining the survival probability for known values of L/E allows to determine Θ_{13} in dependence of Δm^2. The measurement of Θ_{13} can be significantly improved by using two identical detectors at different distances: a near detector to monitor the unoscillated reactor-$\bar{\nu}_e$-flux and a far detector to observe the disappearance effect. The direct comparison between near and far detector allows to perform a relative measurement, which reduces significantly systematic errors regarding $\bar{\nu}$-flux, as well as detector response.

4. Experimental Setup of Double Chooz (DC)

The Double Chooz Experiment is located in Chooz (northern France, Ardennes) at a commercial nuclear power-plant, which operates two closely neighboring reactor-cores with $4.25\, GW_{th}$ each. DC uses two identical detectors installed in two shallow depth underground laboratories. The far-detector(FD) site (formerly used for the CHOOZ-Experiment) is situated $\approx 1050\,\mathrm{m}$ from the cores and offers a shielding of 300 m.w.e. The near-detector(ND) lab will have a distance of $\approx 400\,\mathrm{m}$ and will offer an overburden of 130 m.w.e. Both detectors have the same multi-layered design consisting of four cylindrical and concentric vessels surrounded by a passive steel-shielding. Each detector is additionally covered by an active muon-veto made of crosslayered plastic-scintillator stripes. The individual vessels, their details and the used liquid scintillators are described in the figure below, showing a cut through the far-detector-setup.



The installation of the far-detector was successfully finished in December 2010, and was followed by a filling and commissioning phase until April, 12^{th} 2011, allowing DC to acquire a first set of preliminary data, which will be partially presented in the next section. The construction works for the near-detector laboratory started in April and will allow an installation of the ND early next year. Data taking with both detectors is expected for beginning of 2013 enabling DC to increase its sensitivity for $\sin^2(2\Theta_{13})$ down to 0.03 after four years of data taking with both detectors (see figure 6).

5. Preliminary Data

The first set of data was taken between April and August 2011 with an total efficiency of over 80% covering a time span of 120 days. The FD-performance was tested with calibration sources and cosmic muons demonstrating a well working and stable detector-setup.

μ-correlated data indicates a stable neutron-capture rate in the inner detector, as well as a very good synchronisation between inner- and outer-detector. Vetoing μ-correlated events allows to investigate single-rates in the prompt and delayed energy window (PEW:[0.7-12] MeV, DEW:[6-12] MeV) . Observed rates were 10 Hz in PEW and 0.1 Hz in DEW preliminarily certifying a very low accidental background rate. The search for neutrino *candidates* ($\bar{\nu}$+background) applys several selection cuts searching for a coincident event in PEW and DEW within a time window of 100 μs vetoing all μ-correlated events. Events generated via instrumental light emitted by PMT's are efficiently removed via pulse-shape discrimination. This analysis revealed $\approx$ 4000 observed $\bar{\nu}_e$-candidates, which exceeds already the statistics of CHOOZ[3].

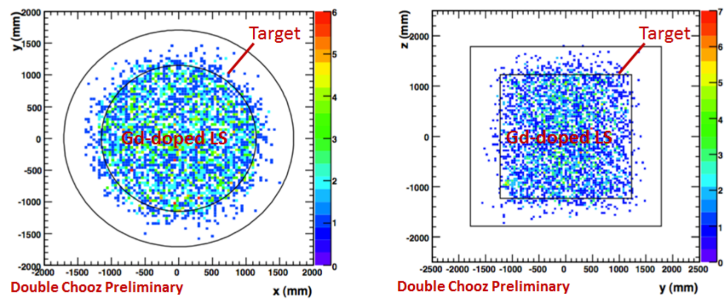


Figure 3: 2d-vertex-reconstruction of neutrino-candidates in the DC-far-inner-detector. top-view(left), front-view(right).

A spacial reconstruction of these $\bar{\nu}_e$-candidates is presented in figure 3 displaying a top and side view of Target and Gamma-Catcher. The color-code depicts the number of hits indicating a homogeneous distribution of $\bar{\nu}_e$-candidates in the Gd-doped target region within the uncertainty of the reconstruction. The time distribution of these events is presented in figure 4 showing the observed neutrino rate per day over 120 days of data taking.

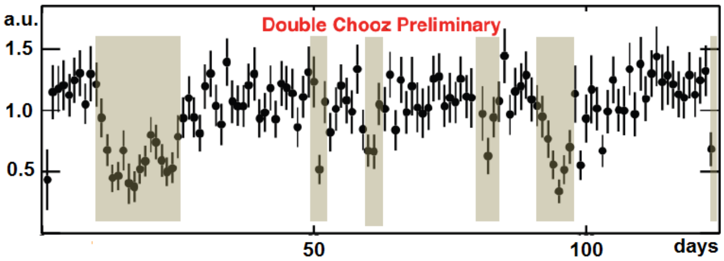


Figure 4: $\bar{\nu}$-candidate rate per day over 120 days of data taking shown in arbitrary units. The shaded boxes indicate one-reactor-off times.

The shaded boxes mark officially released one-reactor-off periods clearly indicating the sensitivity of the FD to $\bar{\nu}_e$-flux variations due to reactor power variations. Figure 5 presents the observed PMT-charge spectrum of μ-correlated n-captures in the inner detector. It shows n-capture peaks on Hydrogen (≈ 2.2 MeV) in the inner detector and on Gadolinium (≈ 8.3 MeV) exclusively in the target; additionally an indication of neutron capture on Carbon ($\approx$3-5 MeV) is observed. Figure 6 shows a revised sensitivity-plot for DC assuming $\sin^2(2\Theta_{13}) = 0$ with 90% CL; The blue curve indicates the expected sensitiviy of DC with the FD only, respectively FD+ND operating in parallel starting from 2013. The red arrow indicates the best-fit value for $\sin^2(2\Theta_{13}) = 0.11$ lately published by the T2K-collaboration[4].

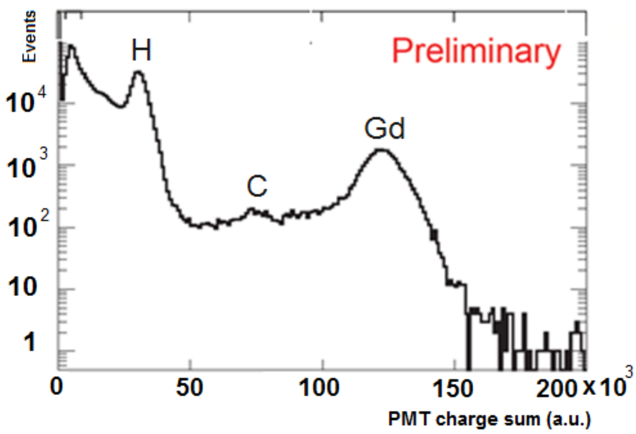


Figure 5: Muon-correlated neutron-capture events in the inner detector on Hydrogen ($\approx$2.2 MeV), Carbon ($\approx$3-5 MeV) and Gadolinium ($\approx$8.3 MeV) with preliminary energy reconstruction.

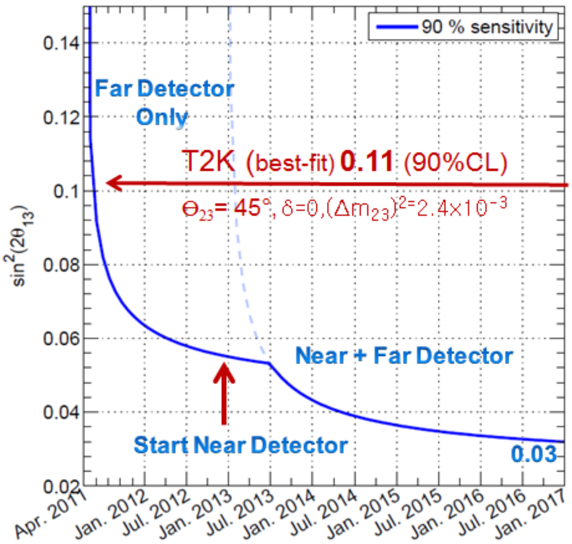


Figure 6: Revised sensitivity-plot for the DC-Experiment with 90% CL for $\sin^2(2\Theta_{13}) = 0$.

6. Conclusion

The Double Chooz Collaboration successfully finished the installation of the far-detector and started data taking in April 2011. First performance tests showed a stable detector set up with low backgrounds. A preliminary data analysis of the first 120 days allows to present 4000 neutrino candidates. Calibration efforts are ongoing preventing yet to present a final energy calibration, for which all energy values given in this paper have to be seen as preliminary. More detailed data-analysis and calibration results will be published within this year. The 2011-data will furthermore allow to address the current values for $\sin^2(2\Theta_{13})$ coming from the CHOOZ-Experiment and the lately published best fit value of the T2K-Collaboration.

References

[1] P. Adamson et al. [MINOS Collaboration] 2011 arXiv:1108.1509v2 [hep-ex]
[2] S. Abe et al. [KamLAND Collaboration] 2008 Phys.Ref.Lett. Vol. 100, Art.221803
[3] M. Apollonio et al.[CHOOZ Collaboration] 2003 arXiv:hep-ex/0301017v1
[4] K.Abe et al.[T2K Collaboration] 2011 arXiv:1106.2822v2 [hep-ex]