Double Chooz

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Abstract. The goal of the Double Chooz reactor neutrino experiment is to search for the neutrino mixing parameter \( \theta_{13} \). Double Chooz will use two identical detectors at 150 m and 1.05 km distance from the reactor cores. The near detector is used to monitor the reactor \( \bar{\nu}_e \) flux while the second is dedicated to the search for a deviation from the expected \( 1/\text{distance}^2 \) behavior. This two detector concept will allow a relative normalization systematic error of ca. 0.6 %. The expected sensitivity for \( \sin^2 2\theta_{13} \) is then in the range 0.02 – 0.03 after three years of data taking. The antineutrinos will be detected in a liquid scintillator through the capture on protons followed by a gamma cascade, produced by the neutron capture on Gd.

1. Introduction
The neutrino flavor eigenstates are related to the mass eigenstates through the neutrino mixing matrix which can be parameterized by three mixing angles and CP violating phases. The current best upper limit on the last unknown mixing angle \( \theta_{13} \) is given by the Chooz reactor neutrino experiment [1]. The new Double Chooz experiment aims to find \( \theta_{13} \) or at least improve the current constraint.

The knowledge and the smallness of \( \theta_{13} \) compared to the other mixing angles is fundamental in itself, but \( \theta_{13} \) is also of relevance for three flavour effects, e.g. the leptonic CP violation can only be found for a nonzero value of \( \theta_{13} \). Double Chooz will have an important discovery potential since the predicted values for \( \theta_{13} \) are in many theoretical models close to the current experimental bound. Another way to explore \( \theta_{13} \) are next-generation long baseline neutrino beam experiments. However, in these long baseline experiments there are degeneracies and parameter correlations between \( \theta_{13} \), the CP violating \( \delta \)-phase, the type of the neutrino mass hierarchy and \( \theta_{23} \), whereas reactor neutrino experiments provide a clean information on \( \sin^2 2\theta_{13} \) [2].

The research studied in Double Chooz is also of relevance for the non-proliferation of nuclear weapons and for safeguard applications. The International Atomic Energy Agency (IAEA) is interested in the antineutrino detection at reactors. Intensity and shape of the neutrino spectrum depend on the isotopic composition of the reactor fuel. This allows in principle to measure the Pu content in the reactor and to search for its unauthorized production. Double Chooz will investigate the feasibility of such measurements. \( \beta \)-spectra for various fissile elements will be measured at the ILL in Grenoble within Double Chooz to improve the accuracy in the antineutrino spectra. A measurement of the antineutrino flux can also be used to determine the thermal power of a reactor.
2. The Double Chooz experiment

2.1. Detector concept

A two detector concept was chosen for Double Chooz to reduce the systematical error of the experiment. The near detector at ca. 150 m distance monitors the $\bar{\nu}_e$ flux of the reactor and the far detector will look for the disappearance of the antineutrinos due to a possible oscillation effect. This two detector concept cancels the systematic errors originating from the nuclear reactors. The antineutrinos are detected via the capture on a free proton: $\bar{\nu}_e + p \rightarrow n + e^+$ ($E_{\text{threshold}} = 1.8$ MeV).

Each of the two pressurized water reactors in Chooz (Ardennes, France) operated by the company Électricité de France (EDF) has a thermal power of 4.27 GW. The neutrino laboratory of the first Chooz experiment still exists and will be reused (shielding of 300 m w.e.). For the near lab an artificial overburden of about 60 m w.e. has to be created.

The neutrino target will be 10.3 m$^3$ of Gd-loaded liquid scintillator (1 g/l Gd) enclosed in a cylindrical transparent acrylic vessel. The target volume is surrounded by the so-called $\gamma$-catcher enclosed in a second acrylic vessel. This volume is also filled with a liquid scintillator, but without Gd, to detect gammas that escape from the target volume. The next volume contains a non-scintillating buffer liquid. At the inner wall of this volume the photomultipliers (PMTs) will be mounted. Finally, there will be a muon veto and 17 cm of radiopure steel.

2.2. Sensitivity and background

The goal of Double Chooz is to improve the sensitivity of the original Chooz experiment giving the current best constraint on $\Theta_{13}$ by one order of magnitude down to $\sin^2(2\Theta_{13}) < 0.03$. This will be achieved by reducing the statistical and systematical error of the first Chooz experiment. The statistical error (2.8 % in Chooz) should be reduced in Double Chooz to 0.4 % by a larger target volume (approximately factor two) and a longer period of data taking (3 years compared to few months). Also the systematical error will be reduced significantly essentially due to the two detector concept from 2.7 % to a relative normalization systematic error of 0.6 %. All the errors connected to the reactor that dominated the systematics in Chooz will be negligible in Double Chooz and also the error connected to the detector will improve due to the two detector concept and an advanced technology. Furthermore, a lower background is expected in Double Chooz. Therefore less analysis cuts are needed - only three instead of seven.

The near detector will be operational more than one year after the far detector. With one detector only the sensitivity for $\sin^2 2\Theta_{13}$ is at 0.08 after 1.5 years. With both detectors running together the sensitivity will then further improve down to 0.02 to 0.03 depending on the true value of $\Delta m^2_{\text{atm}}$.

The signature for a neutrino event is a prompt signal of the positron created in the neutrino interaction followed by the neutron capture on Gd after some $\mu$s creating a $\gamma$-shower with about 8 MeV well above the typical energies of radioactive background. There are two types of background: first there is the accidental uncorrelated background realized by a gamma above 1 MeV combined with a neutron like event falling into the time window. Monte Carlo studies have shown that correlated background events created by fast neutrons slowing down in the scintillator and depositing energy of more than 1 MeV before they are captured on the Gd are more critical. The Monte Carlo studies reproduced within the error the result measured in Chooz and is thus reliable. Another type of correlated backgrounds are $\beta$-n-cascades, e.g. by $^9$Li or $^8$He generated by muon spallation on $^{12}$C. In total the estimated background rates are $9 - 23$ events/day for the near and $1 - 2$ events/day for the far detector. These numbers have to be compared to an interaction rate of ca. 4000 events/day in the near and ca. 80 events/day in the far detector.
2.3. Detector components

Double Chooz will use a Gd-loaded liquid scintillator with 1 g/l Gd-loading. As scintillator solvent a PXE/dodecane mixture was chosen at a ratio of 20:80. The admixture of the dodecane reduces the light yield, but it improves the chemical compatibility with the acrylic and increases the number of free protons in the target. Two scintillator formulations are investigated, one based on carboxylic acids and the other on Gd-$\beta$-diketonates to guarantee long-term stability. The carboxylate version is synthesized in a two phase system and stabilized by pH-control. The metal-$\beta$-diketonate is produced as a powder and can be purified by sublimation.

The signal in the Gd-scintillator will be observed by about 500 8” ultra low background PMTs giving a coverage of 13 % (energy resolution at 1 MeV < 10 %). A first level trigger on single pulses above 500 keV will be used and a second level trigger for the neutrino signal when there is a coincidence within 200 $\mu$s. All channels are continuously sampled using 8-bit-flash-ADCs. The dead times that will be measured using a fake event generator are in the per cent range in the far and about 25 % in the near detector.

The two detectors will be calibrated using several gamma, positron and neutron sources. Additionally, the optical properties of the detector will be calibrated and monitored using lasers. The calibration of the target scintillator will be done using an articulated arm whereas wire driven sources are discussed for the region of the gamma catcher and the buffer. The detector response for source positions at various distances of the detector center was simulated for all kind of sources assuming a non-reflective and a reflective surface of the inner wall of the buffer tank.

To reduce the correlated background it is very important to have an efficient muon veto. The tank holding the buffer liquid is surrounded by the inner veto system. In this inner veto ca. 100 PMTs spread on the top, the bottom and at the walls will look at a liquid scintillator. The background rejection is further improved using an additional outer veto made with several layers of gas filled proportional chambers. Prototype counters are designed and tested.

A mockup of the Double Chooz detector was designed and built to find technical solutions for the construction and integration of the detectors. Furthermore, material compatibility and long-term stability of the scintillator will be tested in this 1/5 scale mockup. More than 100 l of a new Gd-loaded scintillator were produced for this test and a filling system was designed and assembled.

3. Conclusions and outlook

The international Double Chooz collaboration with groups from France, Germany, Italy, Russia and the US released a Letter of Intent [3] and a proposal [4]. The experiment has already been approved in France and cooperative work with the company running the reactor (EDF) started. The aim of Double Chooz is to improve the current best limit on $\sin^22\Theta_{13}$ which was set by the original Chooz experiment by approximately one order of magnitude. This can be achieved by a significant reduction of the statistical and systematical error. The detector design is almost complete. If the experiment is fully approved in 2005 the construction of the far detector should start in 2006. Data taking should then begin in 2007 for the far and in 2008 for the near detector. In this case Double Chooz could provide a sensitivity limit of $\sin^22\Theta_{13} < 0.05$ (90 % C.L.) within 2009 and $0.02 - 0.03$ in 2011.

References

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