Double Chooz and non Asian efforts towards θ_{13}

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Abstract. Neutrino oscillation physics is entering a precision measurement area. The smallness of the θ_{13} neutrino mixing angle is still enigmatic and should be resolved. Double Chooz will use two identical detectors near the Chooz nuclear power station to search for a non vanishing θ_{13}, and hopefully open the way to experiments aspiring to discover CP violation in the leptonic sector. The Angra project aims to prevail over the Double Chooz experiment if the third neutrino oscillation channel is not discovered in the forthcoming years.

1. Searching θ_{13} with a new multi-detector reactor neutrino experiment

Nuclear reactors are prolific sources of $\overline{\nu}_e$ having an energy range extending to ten MeV. Reactor neutrino experiments[1] measure the survival probability $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ at a distance L (km) from the source. According to the current set of parameters the survival probability can be expressed by: $P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m_{atm}{}^2\ L/4E)$, if L is less than a few kilometers. It is worth noting that, thanks to the combination of the low energies and the short baselines considered, the modification of the oscillation probability induced by the coherent forward scattering from matter electrons can be neglected. In addition, the disappearance probability does not depend on the CP complex phase. Thus, a middle-baseline reactor neutrino experiment provides a clean determination of $\sin^2(2\theta_{13})$. It is worth noting that the CHOOZ experiment still holds the world best mark on θ_{13}, $\sin^2(2\theta_{13})<0.2$ [2].

The concept of the new generation of reactor experiments is to perform a relative measurement of the neutrino flux and spectrum within the percent precision using state of the art technologies. At least two 'identical' detectors are required in order to significantly improve the CHOOZ sensitivity. The first, located at a few hundred meters from the nuclear cores, monitors the neutrino flux and spectrum before the neutrino oscillation. The others located between 1 and 2 km away from the cores search for a departure from the overall $1/L^2$ behaviour of the neutrino energy spectrum, the signature of oscillation. This new set-up provides a great improvement in the search for a small mixing angle since the reactor neutrino source was the largest source of uncertainties in previous experiments. In addition the exposure (power $\times$ running time) is being increased by a factor of 15 to reduce the statistical error.

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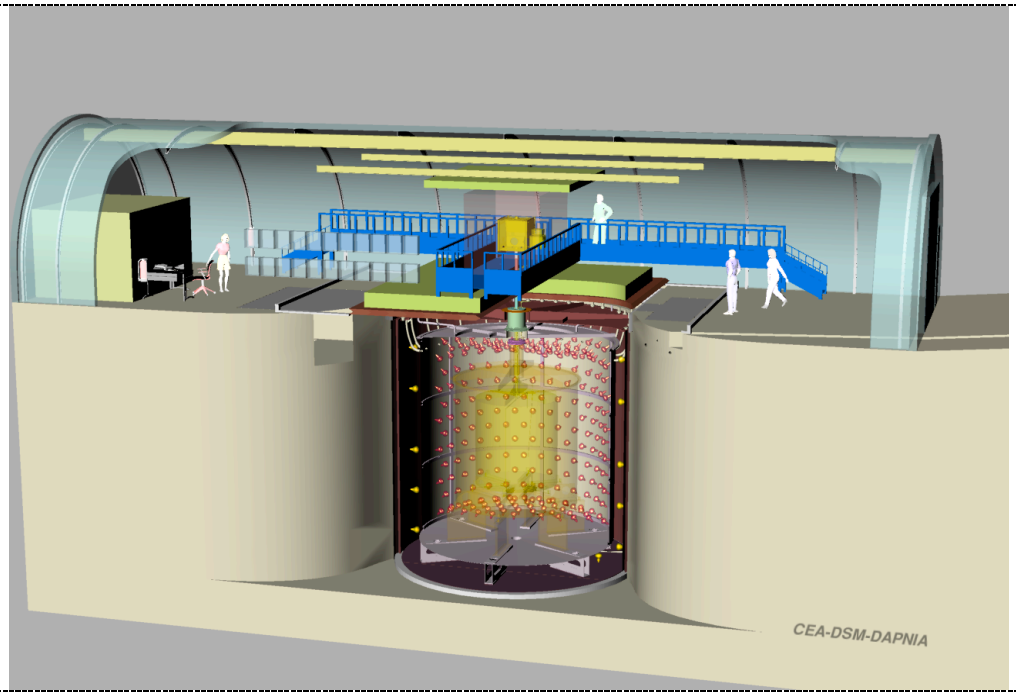

Figure 1. Viewgraph of the Double Chooz detector in the Chooz underground laboratory located 1.050 km from the nuclear cores.

2. Double Chooz

The Double Chooz initiative started early 2003 [3]. The Chooz nuclear power station, operated by the company Electricité de France, was selected because of the availability of the underground neutrino laboratory constructed for the first experiment carried out at Chooz (Figure 1). It is located at 1.05 km from the nuclear cores. Two nuclear cores produce a thermal power of 4.27 GW each. Neutrinos are produced by the β-decays of the unstable nuclei produced by the fissions of ^{235,238}U and ^{239,241}Pu. The absolute normalization and the spectral shape of this neutrino source are known to a precision of 2%. The Double Chooz experiment will employ two almost identical detectors of 10.3 cubic meter fiducial volume. In order eliminate the neutrino spectrum uncertainty as well as to reduce the detector systematic errors, a second detector will be installed 400 m away from the nuclear cores, in a new underground neutrino laboratory, 40 meter deep, located at the end of a 150 m tunnel to be excavated.

Reactor neutrinos will be detected through the inverse β-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$ (1.8 MeV threshold) in organic liquid scintillator doped with 1g/l of a gadolinium complex enhancing the neutron capture. The energy of the incident antineutrino is directly correlated to the kinetic energy of the detected positron. The coincidence of the prompt positron followed by the neutron capture, with a 30 μs time constant, allows a strong rejection of accidental background. In a non oscillation scenario, we expect to detect 55 (550) neutrinos per day inside the far (near) detector, accounting for the detector inefficiencies.

The basic principle of the multi-detector concept is the cancellation of the reactor-induced systematic error. Technically, the two detectors should have a set of very similar parameters to guarantee their identity for the neutrino oscillation search: identical target geometry, a single liquid scintillator batch… In order to correct for the unavoidable differences between the two detector responses, a comprehensive set of calibration systems is being installed, consisting of radioactive sources deployed

in the three inner detector regions, laser light flashers in the inner detector, and LED pulses in the inner detector and in the Veto. In addition, a new detector design has been thought in order to simplify the analysis and to reduce the systematic errors while keeping high statistics and high detection efficiency.

Naturally occurring radioactivity mostly creates random background, defined as an accidental coincidence of a prompt energy deposition in the energy range of the expected prompt positron, followed by a delayed neutron-like event within 100 μs. Selection of high purity materials for detector construction and passive shielding around the active region provide an efficient protection against this type of background. This leads to constraints ranging from 10^{-9} g/g of U/Th for the outermost regions to 10^{-12} g/g of U/Th inside the fiducial volume. Constraints for natural potassium range from 10^{-8} g/g to 10^{-10} g/g correspondingly. It is worth to mention that accidental backgrounds can be correctly measured in situ by varying the time window separation between two consecutive events.

Cosmic ray muons will dominate the trigger rate at both detector sites (6.10^{-5} cm^{-2} s^{-1} & 5.10^{-4} cm^{-2} s^{-1}). Furthermore they are inducing the most critical backgrounds. Muon- induced production of the radioactive isotopes ^{8}He, ^{9}Li and ^{11}Li cannot be correlated to the primary muon interaction since their lifetimes are much longer than the characteristic time between two subsequent muon interactions. These neutron-rich radioisotopes β-decay are mimicking the prompt signal and later evaporate a neutron. This cascade fakes the neutrino signal, and the few events produced each day in the target volume have to be correctly subtracted to deduce the true neutrino event rate. A further source of background comes from neutrons that are produced in the surrounding rocks by cosmic ray muon induced hadronic cascades, not tagged by the inner veto system and being thus invisible. Fast neutrons may then enter the detector, create recoil protons mimicking the prompt signal and be captured by gadolinium nuclei after thermalisation. Such a sequence can be misidentified as a neutrino event. Fortunately this background could be fairly well estimated to one to two counts per day at the far site, from the measurements of the CHOOZ experiment during reactor off periods. Estimation for the near detector site is done by scaling the muon flux by a factor 8, and the mean muon energy by 0.6 (30 GeV/ 60 GeV to the power 0.72).

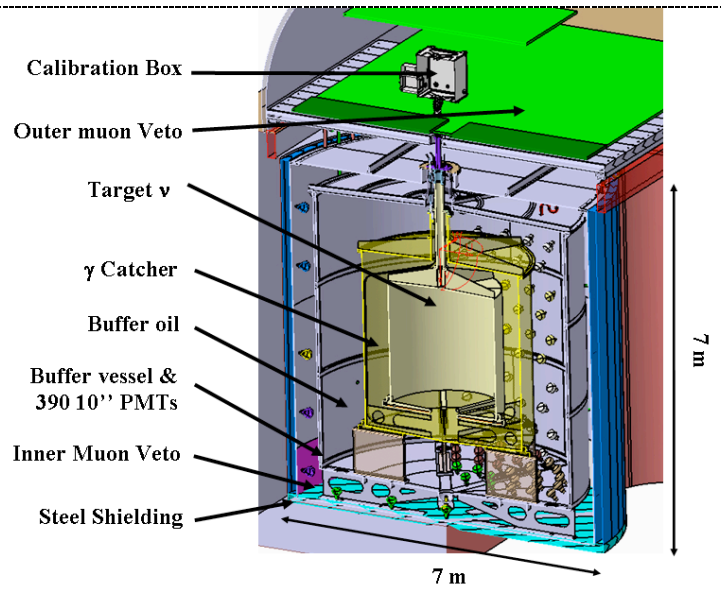

Figure 2. Viewgraph of the Double Chooz detector design. The Target vessels contains 10.3 m^3 of organic liquid scintillator doped with Gd. The full detector is composed of about 250 m^3 of oil and scintillator, and 300 tons of mechanical structure and shielding.

The Double Chooz detector design is an evolution of the CHOOZ detector. The detector core consists of a proton-rich liquid scintillator mixture loaded with gadolinium at a concentration of 1 g/l [3]. The solvent is a phenyl-xylylethane/dodecane mixture at a volume ratio of 20:80, so as to improve the chemical compatibility with the acrylic and to increase the number of free protons in the target. Primary PPO (3-6 g/l) and secondary Bis-MSB (20 mg/l) fluors are also used to shift the photon wavelengths to the suitable range of the photocathodes, and to improve the scintillator transparency. Metal loading of liquid scintillator has been comprehensively studied within the collaboration since 2003, and a new gadolinium encapsulation technique has been carefully tuned for Double Chooz, based on β-diketonate chemistry.

Starting from the centre the detector elements are as follows (Figure 2). The fiducial volume consists of a cylindrical region of 1.15 m radius and 2.8 m height (10.3 m^3) filled with a gadolinium-doped liquid scintillator. The target vessels are built with acrylic plastic material, transparent to visible photons. A second acrylic vessel, the gamma-catcher, encloses the target, providing a 55 cm thick buffer of non-loaded liquid scintillator all around. This scintillating buffer is necessary to fully contain the energy deposition of gamma rays from the neutron capture on gadolinium, as well as the positron annihilation gamma rays in the central region. It also improves the rejection of the fast neutron background. The gamma-catcher vessel is surrounded by a 105 cm thick region of non-scintillating oil so as to reduce the level of accidental background, coming mainly from the radioactivity of the photomultiplier tubes (^{40}K, ^{238}U, ^{232}Th). The oil is contained in an opaque vessel made of thin stainless steel sheets and stiffeners, supports 390 inward facing 10-inch photomultiplier tubes (PMTs), providing 13% photocathode coverage. The inner detector is encapsulated within a muon veto shield, 50 cm thick, and filled with scintillating organic liquid and viewed by 78 8-inch PMTs. It allows the detection of particles entering or leaving the inner detector. Because of space constraint, the 70 cm sand shielding of CHOOZ is replaced by a 15 cm iron layer so as to increase the target volume. Above the detector pit, a highly segmented muon tracker system will identify and locate the muons missed by the inner system, with the purpose of improving the background rejection. The near and far detectors will be "identical" inside the PMTs supporting structure, allowing a relative normalization error of 0.6 %, or less.

Figure 3. View of the 7m x 7m pit at the Chooz neutrino laboratory after the installation of the 15 cm steel shielding (August 2008).

The construction of the Double Chooz first constituents started in 2005. The integration of the first detector at 1 km started in May 2008 with the demagnetization of the 250 tons steel shielding and its installation in the pit during the summer 2008 (Figure 3). In parallel the neutrino laboratory has been completely refurbished (safety installations, ventilation, electricity) and characterized for backgrounds. Beside the neutrino laboratory a 200 m^2 building is being equipped for fluid operation and the first six tanks for the Buffer and Veto liquids have been installed. In the collaboration institutes the gadolinium and the target scintillator are ready for mixing in a single batch for both detectors. All mechanical vessels, the Veto made of steel, the Buffer made of stainless steel, and the acrylics vessels are being manufactured in the industry. The production of the PMTs, magnetic shielding and associated support structure is finished for both detectors, and all the phototubes should be tested before the end of the year. The Inner Veto system is going to be installed at the end of the year. The Outer Veto system is also in production phase.

The Double Chooz experiment offers the world's particle physics community a valuable opportunity to measure the mixing angle θ_{13} within an unrivalled time scale [4]. The data taking will be divided in two phases: a first one with the far detector only, and a second phase with both near- and far-detectors running simultaneously. Double Chooz will be sensitive to $\sin^2(2\theta_{13})>0.06$ after 1.5 year of data taking in phase I, and to $\sin^2(2\theta_{13})>0.03$ or better after 3 years of operation with two detectors (Figures 4, 5).

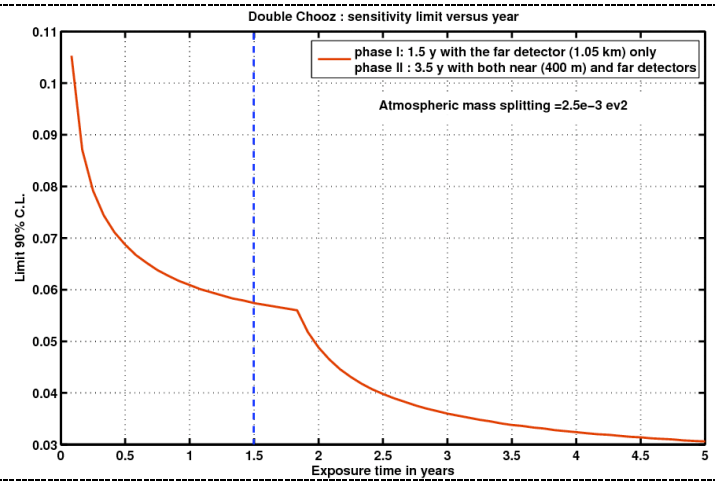

Figure 4. Sensitivity of the Double Chooz experiment [4] versus the data taking time. The experiment will start in 2009 with the far detector only, and will then continue 1.5 years later with both detectors running simultaneously. After 1.5 year an upper limit of $\sin^2(2\theta_{13})<0.06$ is expected at 90% C.L., while the experimental goal with two detector is to reach a sensitivity of $\sin^2(2\theta_{13})>0.03$. Even if $\sin^2(2\theta_{13})$ lie above 0.06 a neutrino oscillation discovery at Double Chooz would be only strongly strengthen after the near detector start.

Beside the reactor neutrino program, new accelerator neutrino beams coupled with off-axis detectors, will search for a ν_e appearance signal leading to similar constraint on θ_{13} [5]. The observation of a ν_e excess in an almost pure ν_μ neutrino beam would be major evidence for a non-vanishing θ_{13}. But in addition to the statistical and systematic uncertainties, correlations and degeneracies between mixing angles, the neutrino masses, and the CP phase degrade the accessible knowledge on θ_{13} [6].If θ_{13} is large, the information gained by Double Chooz could break the parameter correlations and degeneracies and long-baseline off-axis neutrino experiments will be able to search for CP violation in the lepton sector. The reactor and accelerator programs will provide complementary results to better constrain the last

undetermined mixing parameters. Another non-Asian reactor neutrino experiment is being proposed to search for θ_{13}, the Angra project still being at the conceptual stage [7].

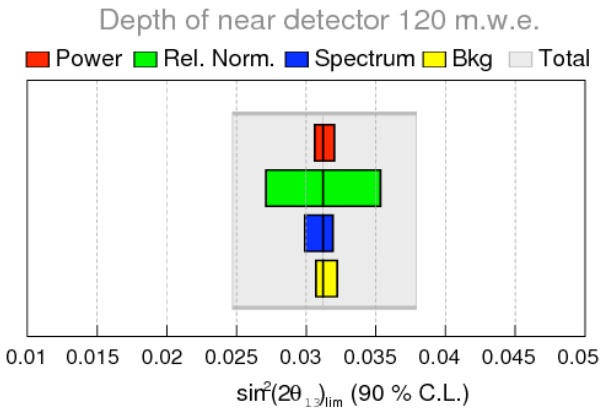

Figure 5. Double Chooz sensitivity as a function of main systematics guesses [4]. Each systematic impact on sensitivity is separately computed and illustrated as ratio R = $\sin^2(2\theta_{13})_{\text{best or worst}} / \sin^2(2\theta_{13})_{\text{baseline}}$. The overall impact changing all three systematics together is also illustrated with the grey area. Best, baseline, and worst systematics guess are considered as : 1%, 2%, 3% for the reactor thermal power uncertainty (red), 0.4%, 0.6%, 0.8% for the relative detector uncertainty (green), 1%, 2%, 3% for the neutrino spectrum uncertainty (blue), and a scaling factor of 0, 1, 2 for the background uncertainty. This computation is done for Δm^2=2.5 10^{-3} eV^2 and for 3 years of data taking with two detectors.

3. Conclusion

Double Chooz is now in construction phase. The first "far" detector is currently being installed in the existing underground laboratory. The detector filling is expected for the summer 2009. We expect a sensitivity similar to the CHOOZ experiment at the end of 2009. The second, identical, "close" detector will be constructed from 2009 in a new neutrino laboratory, located down a 45 m well that will be excavated 400 m from the cores. The Double Chooz experiment promises to start the race towards θ_{13} from 2009. The Angra project in Brazil might take over as a second generation experiment in the future.

4. References

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