The Double Chooz Experiment - toward the high precision measurement in the quest for $\theta_{13}$

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Abstract. The Double Chooz experiment will perform a highly sensitive measurement of the neutrino mixing angle $\sin^2 2\theta_{13}$. The Double Chooz will utilize a two detector design where the near detector provides an "unoscillated" neutrino flux measurement (high count rate, but higher background as well), while the far detector provides the "oscillated" neutrino flux characterized by the lower count rate and lower background level. The signal comparison between the two detectors will be necessary to see the subtle sign of $\theta_{13}$. Double CHOOZ will be built at the site of the original CHOOZ experiment which still provides the best world upper limit on the value of the neutrino mixing angle $\sin^2 2\theta_{13} < 0.2$. We will report on the status of the Double Chooz experiment that will contribute to the discovery of $\theta_{13}$ if above 0.03 or improve the existing limit on $\sin^2 2\theta_{13}$ from 0.2 to 0.03 in just 3 years of running of the Double Chooz experiment. The Double Chooz is currently undergoing the construction of the far detector and will start taking data in April 2010.

1. Introduction
Recent discoveries and measurements in neutrino physics with experiments like KamLAND [1], SNO [2] [3], Superkamiokande [4], and others, have advanced the knowledge of neutrino physics from mere observation to the point where precision measurements are necessary. While the mixing angles $\theta_{sol}$ and $\theta_{atm}$ have been measured to some level of precision, the same has not been true for the angle $\theta_{13}$. The measurement of the mixing angle $\theta_{13}$ is of great importance for the complete understanding of the neutrino oscillations and observability of CP-violation.

A new two-detector reactor neutrino experiment at the CHOOZ site, the Double Chooz experiment, will be sensitive to $\sin^2 2\theta_{13} > 0.03$ (Figure 1 presents limits on the value of $\theta_{13}$ that can be achieved with Double Chooz). In order to successfully measure such a small value of $\sin^2 2\theta_{13}$, the Double Chooz experiment will use near detector to obtain an "unoscillated" flux with high count rate and higher level of backgrounds, and far detector to obtain "oscillated" flux at a lower count rate, but lower background level as well. Although the next generation accelerator experiments will also have the potential to measure $\theta_{13}$, their measurement will be degraded not only by statistical and systematic uncertainties, but also by correlations and degeneracies between $\theta_{13}$, $\theta_{atm}$, sgn($\Delta m^2_{31}$), CP-$\delta$ phase and matter effects [7] [5]. The measurement of $\theta_{13}$ by Double Chooz is much simpler, and does not suffer from the above-mentioned ambiguities. Thus, the Double Chooz experiment will provide a clean, independent measurement of $\theta_{13}$ which will provide necessary robustness to our knowledge of $\theta_{13}$ and neutrino mixing properties [8]. The Double Chooz will start operating with the far detector only, in spring of 2010. Double Chooz will be able to probe 90% of the $\sin^2 2\theta_{13}$ range of interest for the future.
Figure 1. DC sensitivity contours (gray 1 $\sigma$, blue 90%, magenta 2$\sigma$, cyan 3$\sigma$ C.L.) in $(\sin^2 2\theta_{13}, \Delta m^2_{31})$ plane generated for $\sin^2 2\theta_{13} = 0.02$ and $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV$^2$ [10].

Figure 2. $\sin^2 2\theta_{13}$ sensitivity limit for Double Chooz as a function of exposure time. The expected startup for Double Chooz is in 2010.

CP-violation measurement. This experiment can also improve the $\sin^2 2\theta_{13}$ limit with time, and Figure 2 illustrates this.

2. Measurement of $\sin^2(2\theta_{13})$ with reactor anti-neutrinos in Double Chooz
Successful measurement of $\sin^2 2\theta_{13}$ requires a dramatic lowering of the systematic error from 2.7% in CHOOZ to 0.6% in Double Chooz. This will mainly be achieved by a two-detector design that will cancel part of the systematic errors by comparison of two detectors [9] [10]. The anti-neutrino flux in Double Chooz will be provided by the Chooz pressurized water nuclear reactors. Fuel composition as well as dynamics of the fuel burn-up and replacement are known in detail, providing excellent knowledge of the expected anti-neutrino rates that will be used as a cross-check for the measurement obtained by the nearer of two detectors.

Double Chooz will measures the survival probability $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ of the $\bar{\nu}_e$s emitted from the nuclear plant. $\bar{\nu}_e$s are detected in Double Chooz via inverse-beta decay reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The target mass is loaded with gadolinium, which increases energy emitted in neutron capture on gadolinium to 8 MeV. Figure 3 shows an example measurement for a relatively large value of $\sin^2 2\theta_{13} \sim 0.1$.

3. Detector design
The Double Chooz experiment [9] [10] will consist of two identical detectors containing 10.3 m$^3$ of liquid scintillator target doped with 0.1% of Gadolinium (see Figure 4). The far detector will be located at the site of the original CHOOZ detector at 1 km and 1.1 km from the two cores of the Chooz nuclear reactors. The far site has shielding of $\sim$300 mwe of 2,800 kg/m$^3$ rock density. The Chooz near site will be built 400 m from reactor cores with 100 mwe. This will be sufficient to keep the signal to noise ratio above 100 at the near detector site, keeping the associated systematic error much smaller than 1%.

Another important study that has been conducted is the stability of scintillator. As a solvent we will use 20% PXE, 80% Dodecane mixture. The scintillator will be loaded with 0.1% of Gd and it is being developed at Max-Planck-Institut fur Kernphysik (MPIK) at Heidelberg and Gran Sasso National Laboratory (LNGS). Results on the different scintillator formulation are now available on more than 4 years long tests. Even more, heating of the scintillator samples to
40°C has been used to study the aging process in the accelerated manner. Chosen scintillator mixture is Gd-Dmp Beta Dikitonate. Measured attenuation length is a few meters at 420 nm.

Data acquisition system will use Flash-ADC CAEN N(V)1726 modules developed by APC-Paris + CAEN. The modules have 4 channels, wave-form sampling is performed at 500MHz. They posses 8-bit resolution (few PEs/ch for $\bar{\nu}_e$ events). Modules will continuously digitize with zero deadtime (if DAQ can sustain the trigger rate).

Extensive calibration of the detectors are planned for detector related systematic error evaluation and reduction. Target region will be tested in several different ways: deployment of radioactive sources along the detector central axis and throughout the detector volume (University of Alabama (UA), Drexel University and Argonne National Laboratory), laser and LED systems (UA, Tokyo Tech, Oxford University and Illinois Institute of Technology).

4. Conclusion
The construction of the Double Chooz detector has started in the late spring of 2007. As of October 2009, inner veto detector, buffer and gamma catcher have been installed, with target vessel to follow. Detector filling and outer veto installation are planned for winter 2009/2010. The Double Chooz experiment will start taking data in Spring of 2010 and in just 3 years of running, under the condition of achieving projected systematic uncertainty of 0.6%, reach sensitivity to 0.03 value for $\theta_{13}$, providing an $\sim$85% reduction in the existing limit set by Chooz experiment and therefore having an excellent discovery potential.

References
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Figure 3. Far to Near detector spectrum ratio for $\sin^2 2\theta_{13} = 0.1$ and $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{eV}^2$. Error bars are only statistical [10].

Figure 4. The Double Chooz far detector design at the CHOOZ underground site.