The Double Chooz detector

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The Double Chooz experiment will measure neutrino oscillations by comparing the neutrino flux and spectrum in two identical detectors at different distances from a reactor core. Its aim is to make almost an order of magnitude improvement on our knowledge of the last unmeasured neutrino mixing parameter $\sin^2(2\theta_{13})$. This paper presents the detector concept and the main ongoing items for development and optimisation of single systems.

1. PHYSICS MOTIVATIONS

Double Chooz [1] will improve our knowledge of the $\sin^2(2\theta_{13})$ neutrino mixing parameter by almost an order of magnitude on the current limit within an unrivalled time scale and for a modest cost.

The Double Chooz collaboration is composed of institutions from France, Germany, Japan, Russia, Spain, UK, USA and some members from Italy.

The measurement will be based on precise comparison of neutrino spectra in two identical detectors located at different distances from the cores of the Chooz reactor power plant, in the north of France. The previous CHOOZ experiment [2], which provides the current best limit on $\sin^2(2\theta_{13})$, was carried out at the same site. The systematic error on its result was dominated by poor knowledge of neutrino production and interaction; this uncertainty will be largely reduced by the addition of a near detector.

Another important source of systematic error in CHOOZ was the impact of background due to naturally occurring radioactivity. The design of the Double Chooz detectors aims at reducing this background, as detailed in the following.

Construction of the experiment is foreseen to start in 2007 with installation of the far detector, which will take data alone starting in 2008. In few months it will exceed the previous CHOOZ limit. Installation of the near detector will proceed at a distance of about one year. In three years of data taking with both detectors, Double Chooz will explore $\sin^2(2\theta_{13})$ down to 0.02-0.03 at 90% C.L. (for Δm^2=2.5-3.5 $10^{-3}eV^2$).

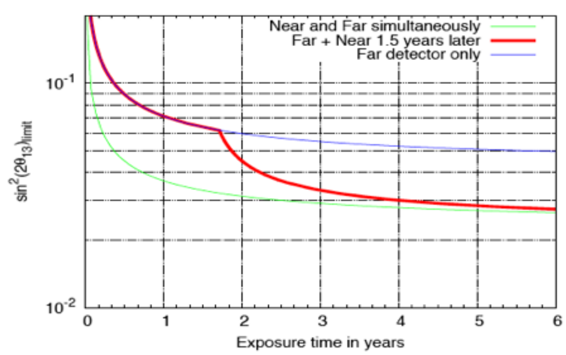

Figure 1. Expected sensitivity (90% C.L.) of Double Chooz to $\sin^2(2\theta_{13})$ as a function of time, assuming a null measurement and $\Delta m^2 = 2.5\,10^{-3}eV^2$. The upper end of the vertical axis is the current upper limit.

2. DETECTOR CONCEPT

Double Chooz will be installed in the proximity of the Chooz two-core (4.27+4.27 GW$_{th}$) nuclear power plant, in the north of France. The "far" detector will look for $\bar{\nu}_e$ disappearance at a distance of 1.05 km from the reactor cores; it will be located in the existing site of the previous CHOOZ experiment, screened from cosmic muons by a natural rock overburden of 300 m.w.e. on average. A "near" detector will be installed at a distance of about 300 m from the cores, to measure the $\bar{\nu}_e$ flux and spectrum from the reactors; a shaft will be excavated, to place the detector under a rock overburden of 80 m.w.e.

Neutrino detection will be based on inverse-beta decay $\bar{\nu}_e p \rightarrow e^+ n$ in liquid scintillator loaded with a high neutron-capture cross-section substance (gadolinium). The signature of the neutrino interaction is the delayed conicidence of the photons from the prompt annihilation of the positron, which allows to measure the neutrino energy, with a delayed (Δt$\sim$30 μs) photon emission at an energy of about 8 MeV from the neutron capture on the gadolinium.

The detector has been designed to minimise the rate of random background with respect to the previous CHOOZ experiment. Each detector consists of concentric cylinders, each one with a specific function:

- The innermost volume, contained in an acrylic vessel, is the fiducial **neutrino target**, consisting of 10.3 m^3 of Gd-loaded scintillator. It is surrounded by a layer (55 cm thick) of unloaded scintillator, also contained in an acrylic vessel, to reduce the loss in detection efficiency for the neutron capture events occurring near the edge of the target. The acrylic vessels provide a "hardware" definition of the fiducial volume, stable in time and identical between the two detectors, with no need for cuts on the reconstructed vertex position at analysis level, which may be a source of systematics.

- Outside of the active scintillating region is a 1.05 m **buffer** of non-scintillating mineral oil, which shields the target from the radioactivity of the PMT photocatode. The PMTs are installed on the inner wall of the steel tank containing the oil. The current plan foresees the installation of 365 10" PMTs, providing an optical coverage of about 13%, to collect the light from the central scintillating volumes.

- The central detector is surrounded by a cylindrical **veto** region, with a thickness of 50 cm at the far detector and about twice as much at the near one, filled with scintillator and read out by 80 additional PMTs, to identify muons which pass near the active detector and can create spallation neutrons and to attenuate and identify backgrounds coming from the outside.

- The tank containing the inner veto volume is shielded by 17 cm of steel to protect the detector from the external gamma background. This will replace the 1 m thick layer of low-activity sand which shielded the CHOOZ detector, providing a better background reduction while leaving more room for the inner fiducial volume and for the buffer region.

An additional detector will be placed on top of the main system, to improve the coverage for cosmic muons passing near the detector. This **outer veto** will most likely consist of two crossed-direction planes of plastic scintillators. It will allow for further reduction of spallation neutrons by extending the region covered beyond the edge of the main system, and will improve the tracking capabilities for muons entering the main detector, useful for cosmogenic radioactive isotope studies.

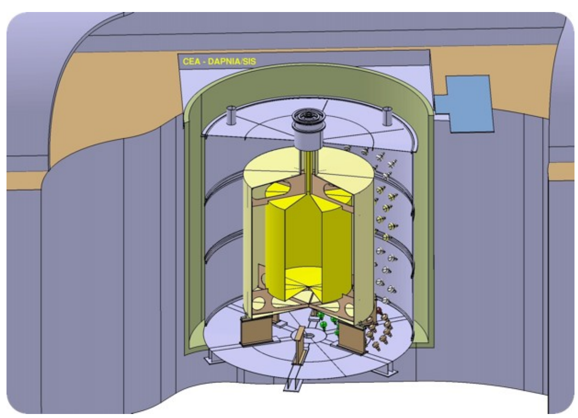

Figure 2. Layout of the Double Chooz far detector.

The near and far detectors will be identical inside the PMT support structure. This will allow a relative normalization systematic error of 0.6%, to be compared with a 2.7% systematic error of the CHOOZ experiment. It is planned to collect more than 60k neutrino interaction events at the far detector, to achieve a statistical uncertainty well below the percent level as well.

3. MAIN R&D ITEMS

Dedicated study and developement have been ongoing for all components of the detector, before starting the construction phase. We focus here on some of the most relevant ones.

3.1. Gd-loaded scintillator

The production of stable high-quality Gd-loaded scintillator is critical for the performance of the experiment. The degradation of the optical quality of the Gd-doped scintillator caused the CHOOZ experiment to stop data taking after one year. For Double Chooz, the long-term stability is even more important, since the two detectors will be installed at different times.

Double Chooz will use a mixture of PXE and dodecane (80:20) with 1 g/l Gd-loading. The Gd-scintillator for both detectors should be produced together as "single batch" to assure identical proton per volume concentrations in both detectors, and to ensure that if there are any aging effects, they are more likely to be the same.

Metal loading of liquid scintillators have been comprehensively studied at MPIK[1] and LNGS[2] for several years. Research with Gd-loaded scintillators at both institutes indicates that suitable scintillators can be produced. Two scintillator formulations have been investigated, one based on carboxylic acids and the other on Gd-β-diketonates. Both systems show good performance and are viable candidate liquid scintillators for the $\bar{\nu}_e$-target.

The long-term stability of the scintillators developed for Double Chooz is investigated by means of spectro-photometric techniques. An example of transmision curves measured at different times over a period of about 400 days is shown in Figure 3. Similar measurements have proven the stability for both formulations and in different ambient conditions.

Industrial production of the complete batch is about to start.

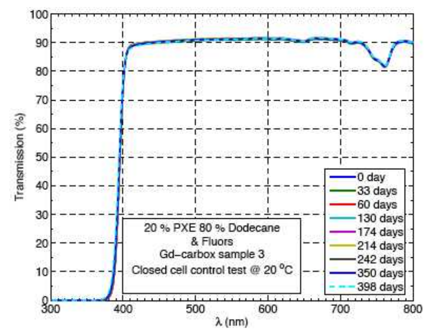

Figure 3. Light transmission as a function of wavelength for a sample of Gd-doped scintillator, measured over a period of almost 400 days.

3.2. Prototype

A 1:5 scale prototype of the detector has been constructed to verify compatibility of the scintillator with the acrylics and other materials, to test the filling system and to validate the mechanical solutions for construction. The inner acrylic structure was filled with Gd-loaded scintillator, the outer volumes with unloaded dodecane-PXE.

The stability of the Gd-loaded scintillator under realistic experimental condition was confirmed over the period of operation of the prototype. In addition, experience was gained on fluid and material handling, identifying the weak points that can be improved for the experiment.

3.3. Electronics boards

The digitization of each photomultiplier signal will be performed by one waveform digitizer channel, to record the pulse shape for possible offline particle identification studies.

The waveform digitizers are built from 8-bit Flash-ADCs operated at 500 MHz. A smart

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memory management allows uninterrupted digitization with zero dead time, as long as the data acquisition system sustains the trigger rate.

The digitizer has been co-developed by APC[3] and CAEN[4]. Double Chooz will use the VME64x version, which houses 8 channels in a 1-unit-wide device with optical fiber data link. At the time of this writing, a prototype of the 4-channel NIM version (N1726) is under test and a protoype of the VME version (V1721) is also available [3]. The production of modules for the experiment will start by 2008.

3.4. Simulation

Detailed simulation studies are being carried out to optimise the detector design and performance, to evaluate the effects of the long-term behaviour of the detector and to define the calibration strategy, which is essential for inter-detector normalisation.

The Double Chooz Monte Carlo simulation package (named "DCGLG4sim") is based on an existing tool [4] for generic liquid scintillator neutrino detectors, built on Geant4 [5]. Major extensions have been developed to implement a detailed micro-physical optical model of both scintillators and photomultiplier tubes. This model accounts for the details of light production, wavelength-shift, absorption, reflection and refraction at all interfaces, including PMTs.

Another subject where simulation studies are essential is the prediction of backgrounds, whose knowledge is a critical issue in evaluating the detector performance. Cosmic-muon induced backgrounds are among the most relevant. Measurement of the cosmic muon flux and angular distributions at the far site were performed before installation of the CHOOZ experiment, however no information was available on the energy spectrum. A dedicated simulation has been carried out [6], accounting for the details of the rock overburden shape and composition: the predicted angular distributions agree well with the past measurements, and in addition the muon spectrum as a function of the incidence angle is accurately predicted.

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4. CONCLUSION

The Double Chooz experiment will improve the sensitivity to the neutrino mixing parameter $\sin^2(2\theta_{13})$ by almost one order of magnitude with respect to the present limit. The multi-detector approach and the focus on background reduction in the detector design will also set the basis for future experiments measuring reactor neutrinos.

The reach of Double Chooz is wider than just neutrino oscillations. Another purpose of the experiment, in collaboration with the International Atomic Energy Agency (IAEA), is to explore the possibility to use neutrinos as a new safeguard tool by monitoring the isotopic composition of the fuel, to ensure that civilian nuclear facilities are not used for military purposes. An antineutrino detector can also provide a measurement of the reactor thermal power with an independent method from the ones used by electric companies.

Installation of the experiment is scheduled to start mid-2007 and the first results are expected in 2008.

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