Neutrino oscillations - the Double Chooz experiment

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Tremendous progress has been achieved in neutrino oscillation physics, but the smallness of the θ_{13} neutrino mixing angle still remains enigmatic. Double Chooz will use two identical detectors near the Chooz nuclear reactor cores to search for a non vanishing θ_{13}, and hopefully open the way to unveiling CP violation in the leptonic sector. The experiment may have some outcome in the field of non- proliferation.

Fact and mysteries in neutrino physics

Invented by W. Pauli in 1930 in order to reconcile the energy conservation with the β-decay experiments, the elusive neutrino was first experimentally discovered by F. Reines and C. Cowan at Savannah River nuclear Plant (South Carolina) in 1956. This opened the door to the use of neutrinos as a sensitive probe of particle physics. This pioneering experiment used the delayed coincidence technique to search for the reaction anti-$\nu_e + p \rightarrow e^+ + n$ where an electron antineutrino interacted with a free proton in a large tank filled with cadmium loaded liquid scintillator [1,2].

All neutrino flavours, ν_e, ν_μ, and ν_τ, are produced in nature, and they have been studied through various channels: atmospheric neutrinos produced in the earth's atmosphere by cosmic rays, neutrinos created in the sun, beamed accelerator neutrinos observed at a few hundred kilometres, and reactor neutrinos emitted by nuclear power stations. These sources have been observed in underground detectors, so as to prevent the contamination of the signal by cosmic ray induced background. Nowadays, the understanding of neutrinos has tremendously improved. Indeed, there is now convincing evidence for flavour conversion of atmospheric, solar, reactor and accelerator neutrinos, and 'oscillation' is the most promising mechanism to explain how neutrinos mix among themselves as they propagate.

The oscillation phenomenon implies that neutrinos have non-vanishing masses, leading to a spectrum of three mass eigenstates, ν_1, ν_2, ν_3 that are the analogues of the charged-lepton mass eigenstates, e, μ, and τ. The neutrino data can thus be described within the framework of a 3 × 3 mixing matrix between the flavour and mass eigenstates:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three mixing angles, labelled θ_{12}, θ_{23}, and θ_{13} characterise the amplitude of the oscillations; moreover a complex CP-violating term entering the formalism could entail neutrino-antineutrino asymmetry (we omitted the two Majorana phases which do not play any role in neutrino oscillations). We note here that θ_{13} is the mixing angle that couples the field of neutrino number 3 (the heaviest) to the electron field. The neutrino mass has a deep implication for the Standard Model of Particle Physics (SM) given that neutrinos are regarded as massless fermions. Consequently there is neither mixing nor CP violation in the lepton sector. The SM has thus to be modified to account for the experimental evidence. The extension of the SM depends on the nature of the physics that gives neutrino mass: either a coupling mimicking the quark masses, providing 'Dirac neutrinos', that conserve the lepton number that distinguishes neutrinos from antineutrinos, or a new mass term that does not conserve the lepton number, providing 'Majorana neutrinos', and preventing the distinction of a neutrino from its antiparticle. Unlike β and rare double-β processes, or the study of the structure formation in the universe, neutrino oscillation experiments cannot access the absolute neutrino mass scale, but only differences between the squared masses: $\Delta m_{21}^2 = m_2^2 - m_1^2 \sim 8 \times 10^{-5}$ eV^2 and $\Delta m_{32}^2 = m_3^2 - m_2^2 \sim 3 \times 10^{-3}$ eV^2 [3,4].

Massive neutrinos provide us with the first evidence of physics beyond the SM [5]. But what is the relevance of knowing θ_{13}? Over the last years, the angle θ_{12} has been measured to be large, $\sin^2(2\theta_{12})\sim0.8$, by the combination of solar and long-baseline reactor neutrino experiments. The angle θ_{23} has been measured to be close to maximum, $\sin^2(2\theta_{23})>0.9$, by atmospheric and long baseline accelerator neutrino experiments. However, we only have an upper limit for the mixing angle θ_{13}, given mainly by the CHOOZ reactor neutrino experiment, $\sin^2(2\theta_{13})<0.2$. The large value of both θ_{12} and θ_{23} indicates a strong difference between leptonic and quark mixings, whereas the smallness of θ_{13} testifies to the peculiarity of the neutrino sector. The value of θ_{13} is of fundamental interest to understand leptonic mixing and to determine the correct neutrino mass model. Knowing the smallness of θ_{13} is also essential to plan for the future experimental programme in neutrino physics, since CP-violating effects directly scale with $\sin^2(2\theta_{13})$. Several questions remain to be answered: What are the neutrino

◀ **Fig. 1:** Picture of the Double Chooz far laboratory hall constructed by EDF, located close the old Chooz-A underground power plant.

masses? Are the neutrinos Majorana particles? What are the neutrino mixing angles? Does the behaviour of neutrinos violate CP? Double Chooz aims to measure the last undetermined mixing angle θ_{13} in order to pave the way for the future measurement of CP violation in the lepton sector.

Reactor neutrinos and CHOOZ

Nuclear reactors are prolific sources of anti-ν_e, with an energy E (MeV) extending out to approximately 10 MeV. Reactor neutrino experiments measure the survival probability P(anti-$\nu_e \rightarrow$ anti-ν_e) over a distance L (km). For distances less than 5 km, this specific oscillation probability can be expressed by

$$P(\text{anti-}\nu_e \rightarrow \text{anti-}\nu_e) = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m_{32}^2 \, L/4E).$$

This two-neutrino formula is a very good approximation, primarily due to the smallness of the ratio $\Delta m_{21}^2/\Delta m_{32}^2$. Furthermore, 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 (the so-called matter effect) can be safely neglected. In addition, the disappearance probability does not depend on the CP complex phase. These latter points support the case that a kilometre-baseline reactor neutrino experiment can lead to a clean measurement of the parameter $\sin^2(2\theta_{13})$, a simple function of θ_{13}.

At the end of the '90s, the CHOOZ experiment was performed to test the hypothesis that the electron neutrino oscillates in the parameter region probed by the atmospheric neutrino experiments $\Delta m_{32}^2 \sim 10^{-3}$ eV^2 [4,6]. The CHOOZ experiment was located in the Ardennes region of France, 1,050 m away from the double-unit Chooz nuclear power station. The detector was located in an underground laboratory below a 100 m rock overburden, providing, for the first time at a reactor, a strong reduction of the cosmic ray induced backgrounds. A homogeneous detector was filled by a 5 ton gadolinium-doped liquid scintillator target, surrounded by a thick active scintillating buffer and a muon veto. The external tank was surrounded by an additional layer of low radioactive sand. This composition of shielding moderates the neutrons induced by muons outside the detector as well as the gamma rays produced by the rocks. Since the two Chooz reactors were commissioned after the start of the experiment, in 1997, there was a unique opportunity to perform an in-situ background measurement. CHOOZ did not observe any evidence of neutrino oscillation, except for small mixing, and excluded $\nu \rightarrow \nu_e$ as an explanation for the atmospheric deficit. But unpredictably, CHOOZ became more famous over the last few years for reason of its bound on θ_{13}, $\sin^2(2\theta_{13})<0.2$, still being the world's best mark [6].

The Double Chooz concept

In order to improve the CHOOZ sensitivity, two (or more) identical detectors close to a power station are required. The first, located at a few hundred meters from the nuclear cores, monitors the neutrino flux and spectrum before the neutrinos oscillate. The second, located between 1 and 2 km away from the cores, searches for a departure from the overall $1/L^2$ behaviour of the neutrino energy spectrum, the footprint of oscillation. Since the reactor neutrino source led to the largest systematic uncertainties in the CHOOZ experiment, this new set-up provides a great improvement in the search for a small mixing angle. Two identical detectors allow a relative comparison, within one percent precision or less using standard technologies. Of course, the statistical error has also to be decreased by a similar amount, leading to an increase of the exposure by a factor of 15 at least.

▲ **Fig. 2:** Picture of the Double Chooz collaboration at the Chooz nuclear power station, on June 2007.

An international union in the French Ardennes

The Double Chooz initiative started in the summer 2003 after an extensive review over several months of the few possible French sites suitable to carry out a new reactor neutrino experiment dedicated to θ_{13}. The Chooz site was selected because of the availability of the underground neutrino laboratory located at 1.05 km from the nuclear cores (Fig.1), funded and constructed by Electricité de France (EDF) for the first experiment carried out at Chooz. This site selection was done in parallel with other similar efforts in Brazil, China, Japan, South-Korea, Russia, Taiwan, and the United States, where 11 sites were being investigated. This international effort led to five international workshops, from 2002 to 2005, which have outlined the challenges and benefits of a new reactor experiment to measure θ_{13} and reviewed the potential of each site [7]. Today the worldwide conditions have changed and only four projects are still being considered: Angra (Brazil), Daya Bay (China), Double Chooz (France), and RENO (Korea). These experiments may be classified into two generations. Double Chooz, and RENO will attempt to probe the value of $\sin^2(2\theta_{13})$ down to 0.02-0.03, whereas Angra and Daya Bay will endeavour to track $\sin^2(2\theta_{13})$ down to 0.01. The first phase will push every single experimental technique to the state of the art. The second generation will require a significant R&D effort since the effective fiducial target mass will be increased by one order of magnitude and moreover systematic and background uncertainties have to be further reduced.

The withdrawal of several of the site candidates led to a reorganisation in participation. Today, the Double Chooz collaboration (Fig.2) is composed of 32 institutions from Brazil, •••

··· France, Germany, Japan, Russia, Spain, United Kingdom and United States, and the experiment has been approved by most of the respective Scientific Councils, standing surety for the launching of the experiment [8].

Neutrino production and detection at Chooz

The antineutrinos used in the experiment are those produced by the pair of reactors located at the Chooz-B nuclear power station operated by the French company Electricité de France. They are located in the Ardennes region, in the northeast of France, very close to the Belgian border, in a meander of the Meuse river (Fig.3). Both nuclear cores are the most powerful type reactors, with a thermal power of 4.27 GW each. Nuclear reactors produce energy through the fissions of ^{235}U and ^{239}Pu, induced by thermal neutrons. The fission fragment nuclei, too rich in neutrons, are particularly unstable and thus decay toward stable nuclei with an average of 6 β-decays per fission, leading to the emission of 6 anti-ν_e. Several hundreds of unstable nuclei are involved in these processes, which makes it very difficult to make accurate predictions. Furthermore the fuel composition evolves with time. In the eighties and nineties, several experiments were performed at a few tens of meters from nuclear reactor cores at Goesgen (Switzerland), Rovno, Krasnoyarsk (Russia), ILL Grenoble, and Bugey (France). From this set of experiments, the absolute normalization and the spectral shape of reactor neutrinos are known to a precision of about 2%.

The Double Chooz experiment will employ two almost identical detectors of 10 cubic meter active size. The laboratory located 1.05 km from the two nuclear cores will be used again. This is the main advantage of this site compared with other locations. In order to cancel the lack of knowledge of the neutrino spectrum, as well as to reduce the set of systematic errors related to the detector, a second device will be installed at about 300 m away from the nuclear cores. Since no high natural hills or underground cavity already exist at this location, a 40 m deep shaft will have to be excavated and equipped.

Reactor antineutrinos have an energy range extending to ten MeV; they are usually detected through the inverse β-decay: anti-$\nu_e + p \rightarrow e^+ + n$ (threshold of 1.8 MeV), with a cross section in the order of 10^{-42} cm^2. Experimentally one detects the very clear signature of the coincidence signal of the prompt positron followed in space, < 1 m, and time, ~100 ms, by the delayed neutron capture, thereby allowing a strong rejection of accidental background. Quite a few gamma rays with a summed energy of about 8 MeV are emitted subsequently to the neutron capture on gadolinium, whereas the gammas from natural radioactive decays hardly deposit more than 2.6 MeV in total. Thus, the addition of gadolinium enhances the neutron tagging, increasing the signal over noise ratio. The energy of the incident antineutrino is directly related to the kinetic energy of the positron, since the neutron is created with a tiny momentum. At Double Chooz, an averaged visible neutrino rate of 55 (550) events per day is expected to be detected inside the far (near) detector, taking into account the various inefficiencies, if no oscillations. Assuming a signal half way from the Chooz bound to zero, the expected oscillation neutrino spectrum is shown in Figure 4.

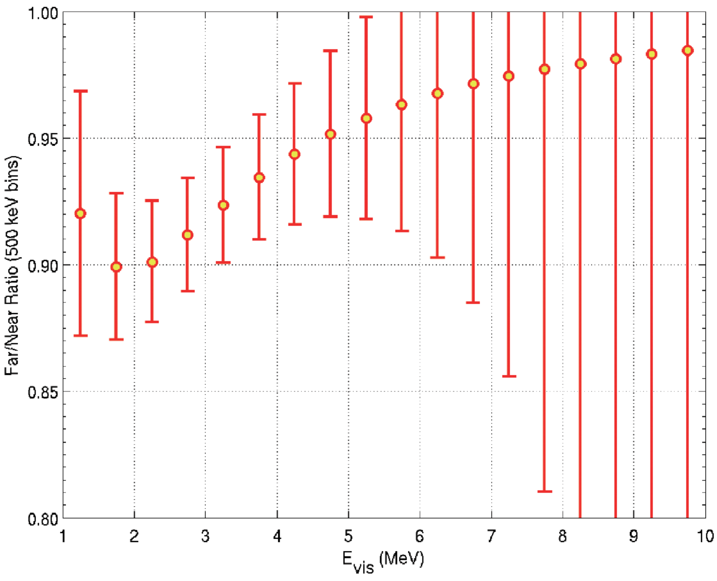
▼ **Fig. 3:** Overview of the Chooz experiment site.

Systematics errors and backgrounds

The basic principle of the multi-detector concept is the cancellation of the reactor-induced systematic error. Though an uncertainty from the neutrino contribution of spent fuel pools remains, it is negligible for Double Chooz. Technically, the two detectors should have a set of very similar parameters to guarantee their conformity for the neutrino oscillation search. For instance, the neutrino rates are proportional to the number of free protons inside the target volumes, which thus has to be experimentally determined with a precision of 0.2%. This constitutes one of the major improvements with respect to CHOOZ. In order to correct for the unavoidable differences between the two detector responses, a comprehensive calibration system is being enforced, consisting of radioactive sources deployed in the different detector regions, laser light flashers, and LED pulses. Meanwhile, the new Double Chooz design has been implemented in order to simplify the analysis and to reduce the systematic errors while keeping high statistics and high detection efficiency. Only three selection cuts will be used for the tagging of the neutrino signal instead of seven for the CHOOZ experiment.

Naturally occurring radioactivity mostly creates accidental background, defined as a random coincidence of a prompt energy deposition similar to the true prompt positron signal, followed by a delayed neutron-like event in the fiducial volume within a one hundred microsecond interval. Selection of high purity materials for detector construction and passive shielding around the active region provide an efficient protection against this type of background. Furthermore, accidentals can be accurately measured in situ.

Cosmic ray muons dominate the trigger rate at the detector sites, and they induce the main source of background. 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, 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 give the true neutrino events. A further source of background comes from neutrons that are produced in the surrounding rocks by radioactivity and in cosmic



▲ **Fig. 4:** Far to Near spectrum ratio for a hypothetical oscillation signal, assuming a true value $\sin^2(2\theta_{13})$=0.1 and Δm_{32}^2= 2.5×10^{-3} eV^2, for 3 years of data taking with both detectors.

ray muon induced hadronic cascades. In the latter case dominant at shallow depth, the primary cosmic ray muon may not penetrate the detector, 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 can 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.

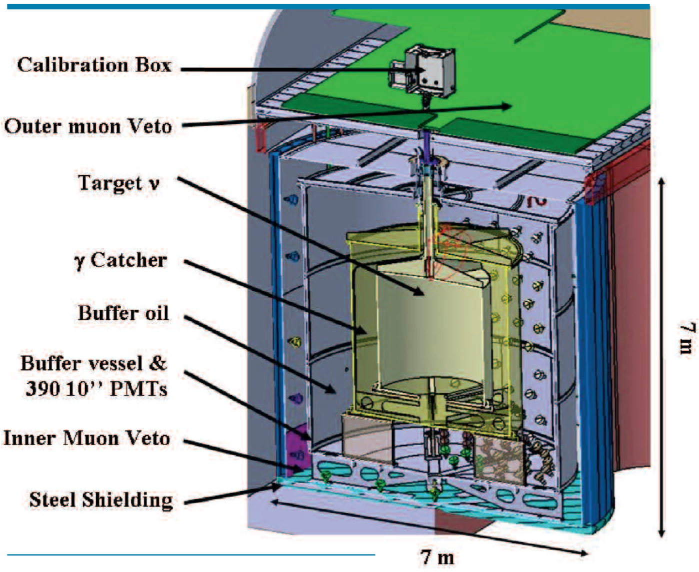
The detectors

The Double Chooz detector design is an evolution of the CHOOZ detector. The heart of the detector consists of a proton-rich liquid scintillator mixture loaded with gadolinium at a concentration of 1 g/l. 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 and secondary components, called "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 scintillators has been comprehensively studied within the collaboration for a few years, and a new complex has been designed for Double Chooz, based on β-diketonate chemistry. Large scale production of 16 tons of target scintillator has already started in order to provide identical neutrino targets for both Double Chooz detectors from 2008 and for several years thereafter.

Starting from the centre the detector elements are as follows (Fig.5). 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 about 70 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.

Sensitivity, competition and complementarity

Two other new reactor neutrino experiments are being prepared to search for θ_{13}: Daya Bay in China, and RENO in Korea, the Angra project still being at the conceptual stage. Daya Bay is an experiment composed of institutions from China, Taiwan, the United States, and Russia. It will be located in the Guang-Dong Province, on the site of the Daya Bay nuclear power station. This consists of two pairs of twin reactors, while an additional pair of reactors is currently under construction. Each core has a thermal power of 2.9 GW. In the full installation setup, 3.3 km of tunnel and 3 laboratories have to be excavated in order to accommodate 8 detector modules containing a fiducial volume of 20 tons of gadolinium-loaded scintillator each. With a systematic uncertainty goal of 0.4%, the Daya Bay collaboration aims to reach a sensitivity of $\sin^2(2\theta_{13})$~0.01 [9,10]. The RENO experiment will be located close to the Yonggwang nuclear power plant in Korea, about •••



▲ **Fig. 5:** The Double Chooz detector layout.

••• 400 km south of Seoul. The power plant is a complex of six reactors, equally distributed on a straight segment extending over 1.5 km, each of them producing a thermal power of 2.73 GW. Two neutrino laboratories have to be built and equipped in order to host the detectors. Both laboratories will be located at the edge of two tunnels to be excavated. With identical systematic errors as in Double Chooz, RENO could obtain a sensitivity of $\sin^2(2\theta_{13})<0.025$ after 3 years of data taking [7,10].

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} [11]. The observation of a ν_e excess in an almost pure nm 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} [12].

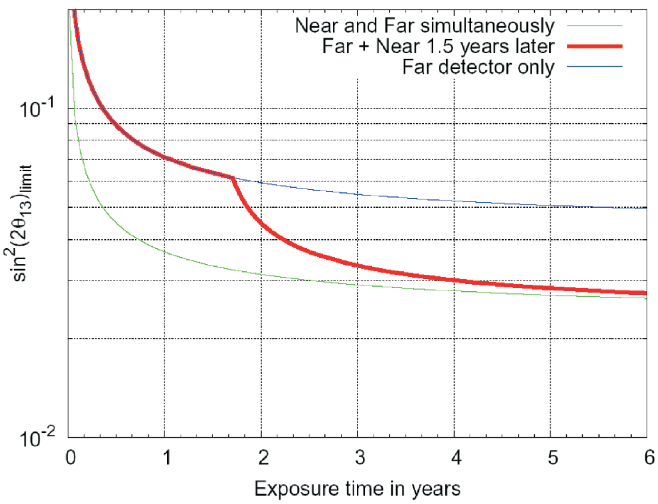
The Double Chooz experiment offers the world's particle-physics community a valuable opportunity to measure the mixing angle θ_{13} within an unrivalled time scale. The data taking will be divided in two phases: a first one with the far detector only, and a second phase with both near- and far-detectors 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 (Fig.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.

Non-proliferation

In the past, neutrino experiments have only been used for fundamental research. Today, thanks to the extraordinary progress of the field, neutrinos could be useful for Society. The International Atomic Energy Agency (IAEA) works with its member states to promote safe, secure and peaceful nuclear technologies. One of its missions is to make sure that safeguarded nuclear material and activities are not used for military purposes. In a situation of international tension, neutrino detectors could help the IAEA to verify the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), signed by 145 states around the world.

In a pressurized water reactor the initial fuel consists of enriched uranium rods, with a ^{235}U content typically of 3.5%, the rest being ^{238}U. As soon as the reactor is operating, reactions of neutron capture on ^{238}U build up ^{239}Pu and ^{241}Pu, producing around 200 kg of plutonium per year. But in these processes the number of antineutrinos per fission from ^{239}Pu is less than from ^{235}U, and the energy released larger by 5%. This sizeable difference offers a handle to monitor changes in the relative amounts of ^{235}U and ^{239}Pu in the core. Combined with the high penetration power of antineutrinos, this provides a new mean to make remote, non-intrusive measurements of plutonium content in reactors. A two cubic meter neutrino detector located at a few tens of meters from a nuclear core, coupled with the well-understood principles that govern the evolution of the nuclear core in time, could in principle monitor nuclear reactor cores non-intrusively, robustly and automatically at a level of accuracy of a few percent. Double Chooz will be a research laboratory with a very high sensitivity to study neutrino oscillations, and a million of events is expected in the near detector. These huge statistics could be exploited to help the IAEA in its Safeguards missions since the near detector will perform a measurement of the antineutrino flux and its energy spectrum with an unprecedented accuracy. This will provide the precious input to undertake a feasibility study of the detection of antineutrinos for safeguards applications by testing the potential of neutrinos to detect various diversion scenarios. In the future, Double Chooz data could serve as a benchmark of this new monitoring technique.

▼ **Fig. 6:** Sensitivity of the Double Chooz experiment after its start in 2008.



Conclusion

Double Chooz is now moving towards the construction phase. The first "far" detector will be installed in the existing underground laboratory at the beginning of 2008. 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 300 m from the cores. The Double Chooz experiment promises to lead the race towards θ_{13} from the end of 2008, and to open the field of non-proliferation neutrino applied physics. ■

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