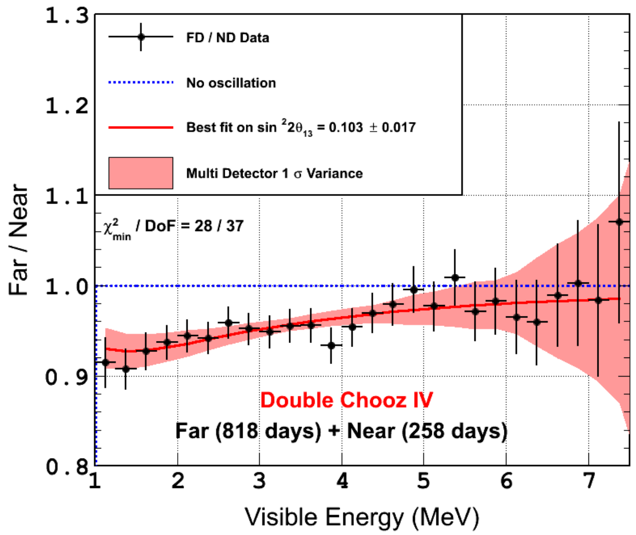

Near to far detector ratio of energy spectra. The expectation with (red line) and without (dashed blue) neutrino oscillations is shown together with the data points (black).

terized at the MPIK and prepared for their integration into the experiment. Moreover, MPIK strongly contributed in Monte Carlo simulation studies and the data analysis.

The liquid scintillators consist of organic compounds. The main difficulty in the production of a Gd-LS is to find a Gd compound, which is soluble in an organic liquid. Here, this was achieved by a complex compound using beta-diketones. A number of requirements must be fulfilled by the Gd-LS: stability for several years, compatibility with the materials in contact, radiochemical purity and suitable optical properties. The scintillator must produce sufficient visible light per event. At the same time, it must be as transparent as possible for this light in order that most of the light arrives at the PMTs.

In each detector 390 PMTs record the light emitted by the scintillator. In close cooperation with Japanese scientists and the RWTH Aachen 800 PMTs have been characterized with respect to its features like, for example, quantum efficiency, quality of the signal and time resolution. For this task a test rig in a light-protected Faraday cage was set up allowing to characterize 30 PMTs simultaneously. As regards simulation and data analysis, the focus of MPIK was on the optical modelling of light production and propagation in the detector, the determination of the energy scale and on studies of the detection efficiency.

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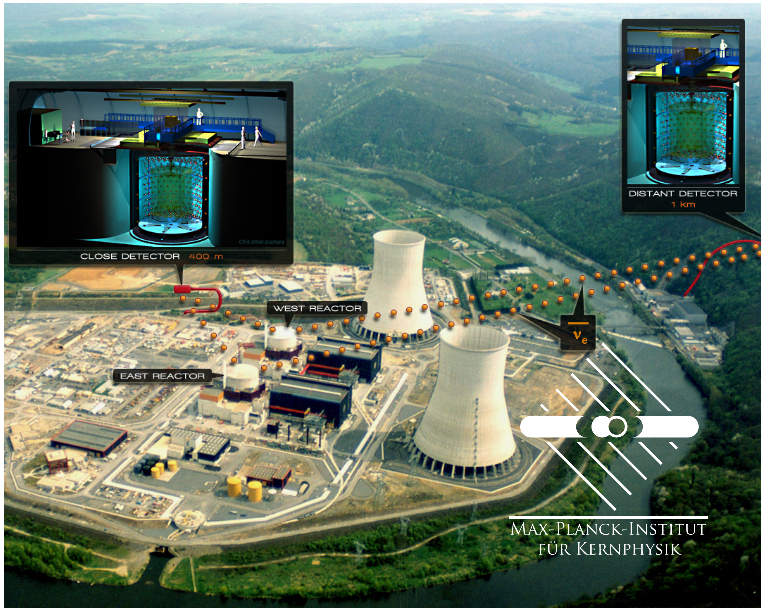
The Max-Planck-Institut für Kernphysik (MPIK) is one of 84 institutes and research establishments of the Max-Planck-Gesellschaft. The MPIK does basic experimental and theoretical research in the fields of Astroparticle Physics and Quantum Dynamics.

MAX-PLANCK-GESELLSCHAFT

Double Chooz

The third mixing angle of the neutrinos



Double Chooz

The third mixing angle of the neutrinos

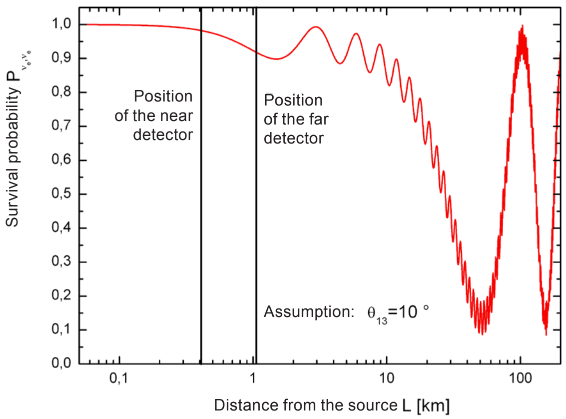
The Double Chooz experiment investigates the remarkable property of neutrinos to convert from one type (flavour) into another. The experiment is performed in the framework of an international collaboration at a nuclear power plant, where a large number of antineutrinos is produced in nuclear processes. In order to determine the conversion probability, two practically identical detectors were built at different distances to the reactor. Neutrinos very rarely react with matter and their conversion probability is low. Starting from 2011 the measurement of antineutrinos took about 7 years to detect a sufficient number of neutrinos to determine the conversion probability at high precision.

Neutrinos

Neutrinos are elementary particles which occur as three different flavours: electron neutrino, muon neutrino and tau neutrino. For each neutrino, there is also an antineutrino. Large experimental progress has been achieved in recent years: It is known, that neutrinos can convert from one flavour into another. To describe the probabilities of these conversions, besides others, the so-called mixing angles are required. All of the three known mixing angles have been determined by now. The Double Chooz experiment already played a major role in the measurement of the third and smallest of the mixing angles. The result is an important step towards a comprehensive understanding of neutrinos and the underlying theoretical models. Double Chooz is also a key experiment for future experiments with neutrino beams searching for the leptonic CP violation.

Concept of the Double Chooz Experiment

The radioactive decay of fission products in a nuclear reactor produces electron antineutrinos as a by-product, escaping in all directions. One of two detectors is placed relatively close to the reactor. On their way to this near detector, the antineutrinos have not yet the possibility to convert into another flavour. In contrast, the second detector is placed at a larger distance, where conversions become more probable. The detectors are able to measure exclusively the electron antineutrinos produced in the reactor. If less neutrinos than expected due to the distance-induced dilution are observed by the far detector, it can be assumed that a part of the electron antineutrinos have converted into another flavour. The conversion probability is deduced from a comparison of the number of neutrino events in the far detector compared the number of neutrino events in the near detector.



Survival probability (= one minus conversion probability) of electron antineutrinos assuming that the value of the sought-after mixing angle is 10°.

Principle of the Detector

The detector consists of several parts, which fulfil special requirements. In the innermost of the detector, the neutrino reactions are detected using a liquid scintillator. In this reaction, a neutrino hits a proton generating a neutron and a positron (the antiparticle of the electron).

Both reaction products are recorded in order to obtain a clearly defined neutrino signal: The positron annihilates together with an electron from the surroundings thereby producing two highly energetic photons. To capture the neutron, the scintillator contains gadolinium. Highly energetic photons are also emitted in this capture process, but somewhat delayed with respect to the positron signal. In the liquid scintillator that is contained in the inner two compartments of the detector, the energy of the photons is successively converted to finally obtain visible light. This light is detected by photomultiplier tubes. Photomultipliers are devices which convert single photons in the visible region into an electrical signal.

The outer part of the detector serves as a shielding against radioactive radiation from the environment. The fourth compartment is used to suppress the background. Particularly cosmic muons, which could interfere with the measurement, are recorded in this part of the detector.

The PMTs and acrylic vessels in the Double Chooz detector.

Double Chooz Results

First results based on measurements with one detector only were already published in November 2011. For the first time a reactor neutrino experiment presented an indication of electron antineutrino disappearance at short baselines consistent with neutrino oscillations and a non-vanishing value for the neutrino mixing angle θ_{13}. With the start of the second detector in early 2015 a sizeable improvement in terms of systematics and statistics could be achieved. The no-oscillation hypothesis and a zero value for $\sin^2(2\theta_{13})$ can now be excluded at a probability of more than 6 standard deviations. In the analysis the neutrino rate as well as the shape information of the measured neutrino energy spectrum are included. The good understanding of the detectors and background control allows to not only analyze neutron captures on gadolinium, but also to include the more challenging neutron captures on hydrogen nuclei in the oscillation analysis.

Double Chooz and the MPIK

The MPIK group as one of the initiators of the experiment developed a novel, stable gadolinium-loaded liquid scintillator (Gd-LS) for the experiment. Furthermore, a large part of the photomultipliers (PMTs) has been tested and charac-