論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Measurement of theta13 in reactor neutrino oscillation with the Double Chooz near and far detectors
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出典(和文)	学位:博士(理学), 学位授与機関:東京工業大学, 報告番号:甲第10611号, 授与年月日:2017年9月20日, 学位の種別:課程博士, 審査員:久世 正弘,柴田 利明,中村 隆司,陣内 修,宗宮 健太郎
Citation(English)	Degree:Doctor (Science), Conferring organization: Tokyo Institute of Technology, Report number:甲第10611号, Conferred date:2017/9/20, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Thesis Outline

The properties and interactions of elementary particles are described by the so-called Standard Model. In the Standard Model elementary particles that make up matter are divided into two main categories: quarks, which take part in strong interactions, and leptons, which only interact via the electromagnetic and weak interactions. Neutrinos are elementary particles of the lepton family. They are electrically neutral and only interact via the weak interaction with a very small interaction cross-section. Neutrinos are created and annihilated in three flavor states (ν_e, ν_μ, ν_τ), which are eigenstates of the weak interaction. Each flavor state can be represented as a coherent superposition of three mass eigenstates (ν_1, ν_2, ν_3) with non-degenerate masses m_1, m_2, m_3. While propagating through vacuum or matter, neutrinos can experience transitions between flavor states (called neutrino oscillations), given the mixing between different flavors and the neutrino masses are non-zero. Neutrino oscillation is described by six independent parameters: three mixing angles θ_{12}, θ_{23}, θ_{13}, two squared mass differences Δm^2_{31}, Δm^2_{21} and a CP violating phase δ_{CP}. The phenomenon of neutrino oscillation has been experimentally observed, proving that the mixing angles and the neutrino masses are non-zero. The smallest of the mixing angles, θ_{13}, was the last to be measured. Best precision on θ_{13} is achieved by reactor neutrino experiments. Nuclear reactors are powerful sources of electron anti-neutrinos, which are produced in the chain of beta decays following a nuclear fission reaction. An average of six neutrinos are produced with each fission reaction. Reactor neutrino experiments extract information about the mixing angle θ_{13} by comparing the neutrino flux and energy spectra measured with detectors at different distances from the reactor cores. Neutrino oscillation probability depends on the distance traveled by the neutrino and the neutrino energy, therefore the neutrino flux and energy spectra are different at different distances from the reactor cores, and the difference is proportional to the observable $\sin^2 2\theta_{13}$.

Double Chooz is a reactor neutrino experiment measuring electron anti-neutrinos produced in the two reactor cores of the Chooz nuclear power plant in Northern France with two large liquid scintillator detectors. The Double Chooz detectors consist of an Inner Detector (ID), which detects neutrino interactions, and sub-detectors (Inner Veto and Outer veto) for background identification surrounding the ID. The ID is made up of three concentric cylindrical vessels, which are called (from the inside out) the Neutrino Target (NT), Gamma Catcher (GC), and Buffer. The NT is an acrylic vessel filled with 10 m^3 of Gadolinium-loaded liquid scintillator. The GC is also an acrylic vessel filled with 22 m^3 of non-loaded liquid scintillator. The Buffer is a stainless steel vessel filled with non-scintillating mineral oil with 390 low-background 10 in photomultiplier tubes (PMTs) installed on its walls. When an interaction takes place within the ID volume, the deposited energy causes the scintillator liquid to produce visible light, which is wavelength-shifted, observed by the PMTs and recorded as electric signals.

The Double Chooz Far detector, situated about 1 km away from the reactor cores, has been taking data since April 2011. The Near detector, at approximately 400 m from the reactors, started collecting data in early 2015. Anti-neutrinos are detected via the inverse beta decay (IBD) reaction, in which a neutrino interacts with a proton to produce a neutron and a positron. The IBD reaction is observed in the detectors as a delayed coincidence of a prompt and a delayed signal. The prompt signal is formed by the energy deposited by the positron and two gamma rays released from positron - electron annihilation. The delayed signal is made up of gamma rays released after a neutron capture on a nucleus. Events with neutron captures on Gadolinium are generally preferred, but events with captures on Hydrogen are also used by Double Chooz and other experiments. In the case of captures on Gd the neutron capture time is about 30 microseconds and a total of 8 MeV of energy is released. In the case of H the capture time is 200 microseconds and the delayed signal is a single 2.22 MeV gamma ray. Due to the low energy of the delayed signal, which is well within the range of natural radioactivity, the H analysis is prone to large contaminations of the so-called accidental background. Accidental background is formed by random coincidences of two unrelated signals, mostly two environmental gamma rays and less often an environmental gamma and a spallation neutron capture. The accidental background is dominant in rate in analyses using captures on H and directly affects sensitivity to $\sin^2 2\theta_{13}$.

Before the completion of the Near detector Double Chooz performed data analysis using only Far detector data. In March 2016 Double Chooz presented its first result with multi-detector configuration. This result was based on Gd events. However, after this first presentation, focus was shifted to the combined analysis channel using captures on both Gd and H. By doing this Double Chooz successfully managed to increase signal statistics by ~3 times. A crucial task for the combined analysis is reduction of accidental background. A neural network based tool for accidental background rejection was developed and optimized to work in the Gd and H combined mode with multiple detector configurations. With it we were able to achieve signal MC to accidental background ratio of ~25 in the Far detector and ~250 in the Near, while keeping signal MC detection efficiency at around 85%.

As a part of the work presented in this thesis, a measurement of the mixing angle θ_{13} was performed in the framework of the Gd and H combined, multi-detector analysis. Information about θ_{13} is extracted by a binned chi-squared fit to the energy spectrum of the prompt signal of IBD prompt-delayed pairs. The main analysis result uses the so-called data-to-data fit, which compares Far detector data to Near detector data. A cross-check was done with the data-to-MC fit, comparing data to predictions, and gave consistent results.