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Double Chooz and a history of reactor θ_{13} experiments

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Abstract

This is a contribution paper from the Double Chooz (DC) experiment to the special issue of Nuclear Physics B on the topics of neutrino oscillations, celebrating the recent Nobel prize to Profs. T. Kajita and A.B. McDonald.

DC is a reactor neutrino experiment which measures the last neutrino mixing angle θ_{13}. The DC group presented an indication of disappearance of the reactor neutrinos at a baseline of $\sim$1 km for the first time in 2011 and is improving the measurement of θ_{13}. DC is a pioneering experiment of this research field. In accordance with the nature of this special issue, physics and history of the reactor-θ_{13} experiments, as well as the Double Chooz experiment and its neutrino oscillation analyses, are reviewed.

1. Introduction

It is exciting that Profs. T. Kajita and A.B. McDonald are awarded the Nobel prize in physics for the discovery that neutrinos have finite mass, through neutrino oscillations. It is an evidence

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that the studies of the neutrino oscillation are appreciated for having considerably deepen our understanding of the nature.

In short, Prof. Kajita's study was detecting atmospheric neutrino oscillations [1] and measurement of neutrino oscillation parameters, θ_{23} and Δm^2_{32}. Prof. McDonald's study was identifying the transformation of the flavors of solar neutrinos [2] and measurement of θ_{12} and Δm^2_{21}. The Double Chooz (DC) experiment detects another type of neutrino oscillation using reactor neutrinos at a ~1 km baseline and is measuring a neutrino mixing parameter, θ_{13}. This article is to explain the Double Chooz experiment as a part of the special issue of the Nuclear Physics B, for celebrating the Nobel prize. The physics and history of the θ_{13} measurement, an overview of the Double Chooz experiment and its results on the neutrino oscillation measurements so far are summarized in the following sections.

2. Neutrino oscillation and θ_{13}

Neutrino oscillation is a phenomenon that a certain neutrino flavor periodically transforms to other flavor state. For the two flavor case, if there is a transition between ν_e and ν_μ, just like the transition between flavor eigenstate quarks, d' and s', the state equation of the neutrinos can be expressed effectively as [3]

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{\gamma}\begin{pmatrix}\mu_e & \tau^*_{e\mu}\\ \tau_{e\mu} & \mu_\mu\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}, \tag{1}$$

where $\tau_{e\mu} = |\tau_{e\mu}|e^{i\phi}$ is the amplitude of the $\nu_e \leftrightarrow \nu_\mu$ cross-transition and μ_e and μ_μ are the amplitudes of the self-transition to the original states $\nu_e \leftrightarrow \nu_e$, $\nu_\mu \leftrightarrow \nu_\mu$. In other words, μ_e and μ_μ are the original masses of ν_e and ν_μ in case $\tau_{e\mu} = 0$. γ is the Lorentz factor which represents the time dilation of the ultra relativistically moving neutrino system. As a result of Eq. (1), the mass eigenstate of the neutrino, ν_1 and ν_2, becomes a mixture of ν_e and ν_μ:

$$\begin{pmatrix}|\nu_1\rangle\\ |\nu_2\rangle\end{pmatrix} = \begin{pmatrix}\cos\theta & -e^{-i\phi}\sin\theta\\ e^{i\phi}\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}|\nu_e\rangle\\ |\nu_\mu\rangle\end{pmatrix}, \tag{2}$$

where θ is called the mixing angle. The relations between the mixing angle, neutrino masses m_1, m_2 and the transition amplitudes are

$$\tan 2\theta = \frac{2|\tau_{e\mu}|}{\mu_\mu - \mu_e} \quad \text{and} \quad \begin{pmatrix}\mu_e\\ \mu_\mu\end{pmatrix} = \begin{pmatrix}\cos^2\theta & \sin^2\theta\\ \sin^2\theta & \cos^2\theta\end{pmatrix}\begin{pmatrix}m_1\\ m_2\end{pmatrix}. \tag{3}$$

The mixing angle is a measure of the ratio of the cross-transition amplitude and the difference of the original masses. μ_e and μ_μ correspond to the observable mass[1] of the ν_e and ν_μ states, respectively, which means that μ_e has been measured to be smaller than ~2 eV by direct neutrino mass measurements [4].

The oscillation probability of $\nu_\mu \to \nu_e$ appearance at baseline L can be calculated as

$$P_{\nu_\mu\to\nu_e}(L) = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu}L, \tag{4}$$

using Eq. (1) with $\gamma = E_\nu/m_\nu$, where $m_\nu = (m_1 + m_2)/2$ is the average neutrino mass. Eq. (4) is the 2-flavor neutrino oscillation formula often used.

[1] If we measure the mass of the ν_e state, the expectation value is $m_1\cos^2\theta + m_2\sin^2\theta$.