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Precision Neutrino Mixing Angle Measurement with the Double Chooz Experiment and Latest Results

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The Double Chooz experiment has been at the forefront of accurately measuring the third neutrino mixing angle θ_{13}. The experiment involves two identical liquid scintillator detectors at 400 m and 1 km baselines from the two nuclear reactors in Chooz, France. To detect the neutrinos, the experiment uses the "Total Neutron Capture" technique to measure the inverse beta decay (IBD) signature, which includes prompt positron annihilation and a delayed neutron capture signal on all possible isotopes available in the detector. The experiment's double detector setup, carefully considering all neutrino rates, energy spectral shapes, and inclusive backgrounds control model, allows for accurate measurement of θ_{13} and a precise characterization of the reactor flux. The latest results from the Double Chooz measurement and advances are presented in this proceeding.

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1. Introduction

In this proceeding, an in-depth exploration of neutrino oscillation formalism is presented, highlighting the work of the Double Chooz experiment and its innovative Total Neutron Capture technique. The experimental methodologies and data analysis strategies employed to advance the understanding of neutrino properties are delved into. Central to this discussion is the latest neutrino mixing angle θ_{13} result, which represents a significant advancement in sensitivity.

2. Neutrino Oscillations

Neutrinos are fundamental particles in the standard model of particle physics. They were initially believed to be massless until the discovery of neutrino oscillation, which refers to their ability to transition into other flavors (ν_e, ν_μ, ν_τ) as a function of their energy and distance traveled. The particle flavors are described as a combination of three mass eigenstates (ν_1, ν_2, ν_3), which explain the propagation of neutrinos. Changes in the flavor composition are described as rotations between the two bases spanned by the mass and flavor eigenstates. These rotations are determined by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), the difference between the squared neutrino masses ($\Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{32}$), and a CP violating phase δ_{CP}, ignoring the Majorana phases [1]. The mixing angles are contained in the so-called U_{PMNS} matrix [2].

The U_{PMNS} matrix can be expressed as:

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

here with $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin_{ij}$. Using this matrix, the survival probability for an initial $\bar{\nu}_e$ can be approximated as:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right) \tag{2}$$

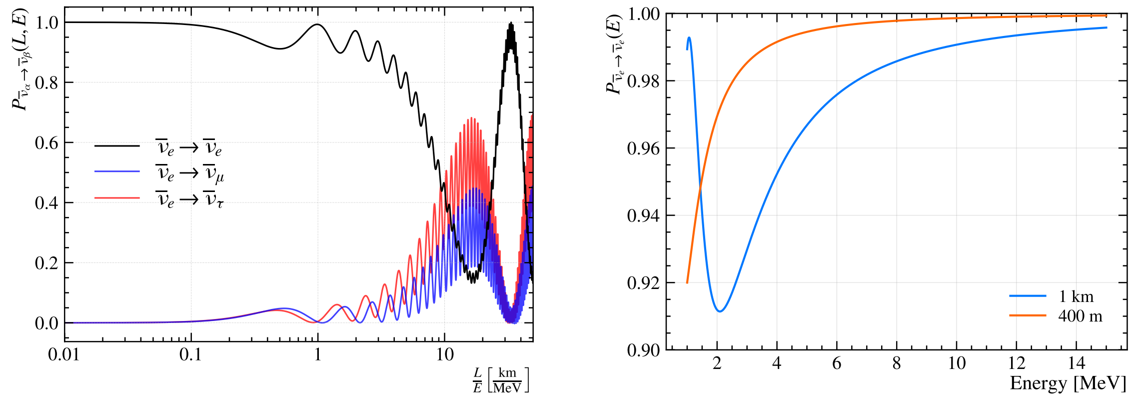
where $\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$ is a mixing weighted mass-squared difference.

For a short baseline and assuming only two neutrino flavor and mass eigenstates, the survival probability for an initial $\bar{\nu}_e$ as a function of distance L and energy E can be approximated as:

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right). \tag{3}$$

The survival probability for an initial $\bar{\nu}_e$ as a function of distance L and energy E is shown in black in figure 1a along with the corresponding transition probabilities for the other flavors.

The Double Chooz experiment measures the neutrino mixing angle θ_{13} by measuring the energy-dependent neutrino rate from the two reactors of the nuclear power plant in Chooz, France. The experiment is conducted at two distances, at approximately 400 m and 1 km, and the effect of neutrino oscillation becomes apparent as an energy-dependent neutrino rate deficit in comparison to the expected spectrum of an isotropic neutrino source. The survival probability for the two distances is shown in figure 1b.



(a) Neutrino Oscillation as a function of distance and energy $\frac{L}{E}$.

(b) Survival probability for two fixed distances as a function of energy.

Figure 1: Neutrino oscillation as a function of energy and distance traveled.

3. The Double Chooz Experiment

The Double Chooz experiment consists of two identical detectors, which are positioned at distances of 400 m and 1 km from the two nuclear reactors situated in Chooz. The power output of these reactors is 8.5 GW, producing a flux of approximately $\sim 10^{21}\,\bar{\nu}_e\,\text{s}^{-1}$ to counteract the neutrino's small cross-section [1]. Figure 2 shows a schematic layout of the experiment and an illustration of the detector structure. The near and far detectors are located in underground laboratories and are shielded against cosmic radiation with 120 and 300 meters of water equivalent (m w.e.) for the near and far detector, respectively [1, 3].

The detectors are designed in a layered structure, consisting of a central ν-target, which is a gadolinium-doped liquid scintillator-filled acrylic vessel. It is surrounded by an undoped liquid scintillator vessel called the γ-catcher, which is further enclosed by a non-scintillating mineral oil volume lined with 390 photomultiplier tubes (PMTs). These PMTs measure the light signals produced by the primary neutrino detection channel, the inverse-beta-decay (IBD)

$$\bar{\nu}_e + p \longrightarrow e^+ + n\ . \tag{4}$$

This reaction occurs when an $\bar{\nu}_e$ interacts with a proton p in the liquid scintillator, producing a positron e^+ and neutron n. The positron annihilates almost immediately, creating a prompt scintillation light signal. The neutron is subsequently captured by a gadolinium or hydrogen nucleus, inducing a gamma-ray cascade and providing a delayed signal. The combination of prompt and delayed signals, in terms of their energy, and spatial and time difference, indicates an antineutrino event. The primary backgrounds of the experiment consist of radioactive ^{9}Li decay and fast neutrons that are induced by atmospheric muons and accidental coincidences of natural radioactivity in the scintillator. To mitigate these effects and accurately isolate genuine neutrino events with a selection efficiency larger than 85 % averaged over the prompt energy spectra, shielding and veto systems, along with sophisticated data analysis techniques like the utilization of an artificial neural network (ANN), are employed [1]. The Total Neutron Capture (TnC) method in the Double Chooz experiment significantly enhances neutrino detection by integrating neutron captures across

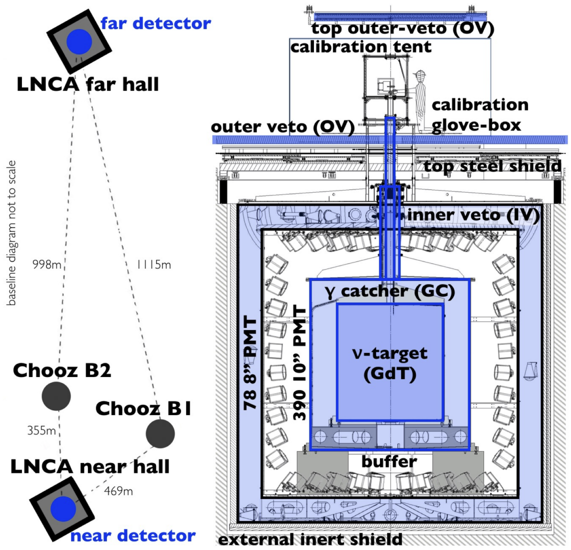


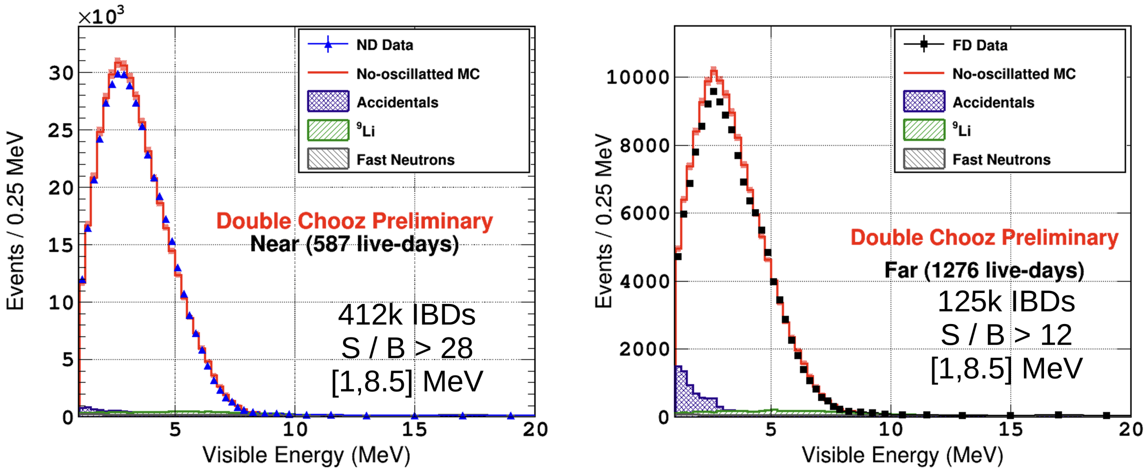
Figure 2: Experimental setup and detector schematics for the Double Chooz experiment [1].

gadolinium and hydrogen, increasing the statistics by a factor of 2.5 and encompassing both the ν-target and γ-catcher regions [1]. This approach boosts statistical sensitivity and minimizes Monte Carlo inaccuracies and boundary effects, leading to a more stable and efficient detection process independent of specific capture details and less affected by variations in element concentrations [1].

4. Measurement of the Neutrino Mixing Angle θ_{13}

The neutrino mixing angle θ_{13} is obtained by comparing the measured reactor neutrino spectrum with the predicted spectrum following Huber [4] and Muller [5], oscillated with the formula described in equation 3 [1]. The neutrino energy is inferred from the reconstructed prompt energy, which is in first order linearly dependent on the initial neutrino energy ($E_{\bar{\nu}_e} \approx E_{e^+} + 0.78\,\mathrm{MeV}$) [1]. The measured prompt energy spectrum for 587 d and 1276 d live-time for the near and far detector respectively, together with the No-Oscillation hypothesis from the forward-folded predicted neutrino spectrum is depicted in figure 3 [1]. The observable deficit in the number of measured neutrino events shows the amplitude in the short baseline survival probability amplitude $\sin^2(2\theta_{13})$ in figure 1a. The ratio between the Null-Hypothesis for both detector data sets is shown in figure 4 where the best-fit model in red with the total systematic uncertainty follows the trend of the data points in black. The distortion at an energy of about 5 MeV is observed by multiple reactor neutrino experiments [1] and is actively being investigated. The best-fit $\sin^2(2\theta_{13})$ value for this Double Chooz data set is [6]

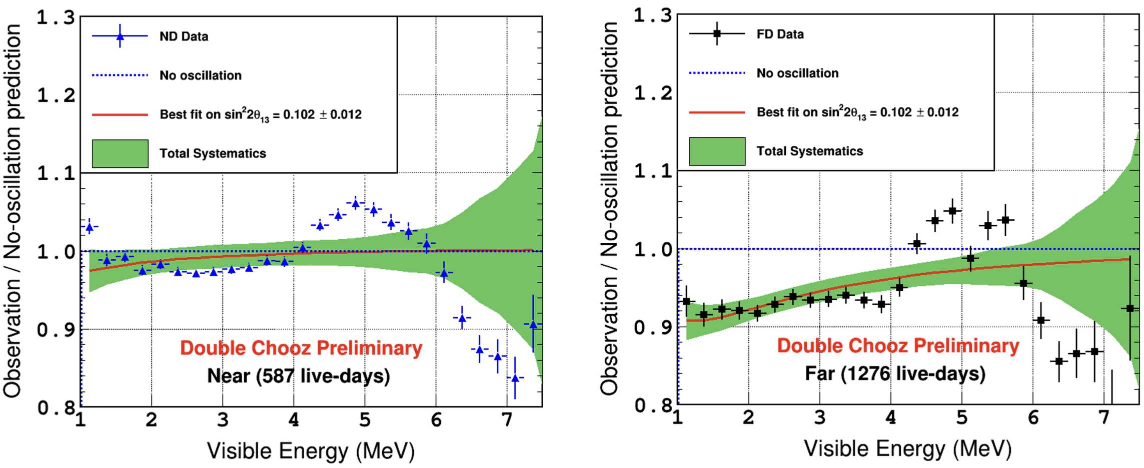
$$\sin^2(2\theta_{13}) = 0.102 \pm 0.011 \;(\text{syst.}) \pm 0.004\,(\text{stat.})\,. \tag{5}$$



(a) Near detector spectrum.

(b) Far detector spectrum.

Figure 3: Measured Double Chooz Data with no oscillation hypothesis and best-fit background predictions for full near and far detector live-time [6].



(a) Near detector ratio.

(b) Far detector ratio.

Figure 4: Ratio of the measurement data and best-fit model prediction to the No-Oscillation hypothesis. [6].

5. Outlook

The Double Chooz experiment aimed to measure the neutrino mixing angle θ_{13} by observing the disappearance of $\bar{\nu}_e$ and measuring the amplitude of the survival probability. One of the significant factors affecting the results is the number of target protons in the γ-catcher vessel. The detector volume was precisely measured during dismantling to understand the systematics better, and it is expected that this will reduce the total uncertainty from $\sigma_{\sin^2(2\theta_{13})}$ = 0.012 to 0.0105 [6]. The final Double Chooz publication is currently being written, along with a single publication on the reactor-off phases and the treatment of the pure background sample with residual reactor neutrino flux. An update on the sterile neutrino analysis using the complete Double Chooz data set is also forthcoming.

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