Abstract

This paper describes the creation of a public data access webpage that will allow people not affiliated with the Double Chooz experiment to understand exactly how the value of $\theta_{13}$ was measured by the experiment. Double Chooz is a two detector neutrino experiment based in Chooz, France that has run since 2011. In this paper, I go into the background of neutrinos and the math behind them. I then talk about the Double Chooz experiment itself. Finally I go into my work done on the public data access webpage.

1 Introduction

1.1 The Standard Model

The Standard Model of particle physics is a theory from the 1970s created to describe fundamental particles and how they interact. We know that all matter is made up of quarks and leptons. Quarks make up protons and neutrons, while leptons include electrons, muons, taus and their neutrino counterparts. Then there are bosons, which are force carriers. While it does answer a lot of questions, the Standard Model is not yet complete. We still don’t know where gravitons, theorized bosons that explain gravity, belong. Another limitation of the Standard Model is where we would find dark matter or dark energy. We know that together they make up approximately 95 percent of the known mass-energy of the universe, but it’s unclear exactly where and how the Standard Model could reflect that. Another limitation of the Standard Model than is beginning to be accounted for is the idea that neutrinos have mass.

1.2 Neutrinos

Neutrinos were first theorized in 1930 by Wolfgang Pauli as tiny massless neutral particles. This observation wasn’t challenged in the following years as scientists strived to learn more about the particles. We learned that the sun emits electron neutrinos then called solar neutrinos. The Standard Solar Model led the way for calculations of how many solar neutrinos we should be seeing. In 1965, the Ray Davis Homestake Experiment was initiated to measure this number. It was confusing when the experiment only found a third of the expected neutrinos. At first, scientists believed that either the Standard Solar Model
or the experiment must be wrong. But as the model was checked repeatedly, more experiments found the same result. It was theorized that neutrinos were changing flavors, or oscillating, and since the experiments had only been set up to measure one flavor, they had been missing the others. In 2001, the Sudbury Neutrino Observatory (SNO) decisively proved this theory of neutrino oscillation correct[2]. SNO built the first detector sensitive enough to measure more than one type of neutrino and saw the total number of neutrinos rise to the theorized amounts. Quantum mechanics allows neutrinos to oscillate only if they have mass, which means that the idea of a neutrino as a massless particle was incorrect.

It has been found that neutrinos, in addition to having three flavor states, have three mass states. There’s a quantum mechanical superposition between the two. In other words, a certain combination of all three mass states is equal to one flavor state as shown in equation 1.

\[ |\nu_\alpha> = \sum_i U_{\alpha i} |\nu_i> \]  \hspace{1cm} (1)

As a neutrino travels, it doesn’t have a strictly defined state. As a result, the equation for neutrino oscillation is in terms of the probability of moving from one specified flavor state to another as shown in equation 2.

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta) \sin^2(1.267\Delta m^2L/E) \]  \hspace{1cm} (2)

This equation, however, is only relevant for a two flavor change. The more realistic three flavor change involves a mixing matrix \( U \) which is made up of different ‘mixing angles’ between the flavors.

\[ U = [A][B][C] \]  \hspace{1cm} (3)

A, B and C each include a different mixing angle. The mixing angles are dependent on the initial and final flavors. These mixing angles replace the \( \theta \) in equation 2.

\[ A = \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \]  \hspace{1cm} (4)

\[ B = \begin{pmatrix} \cos(\theta_{13}) & 0 & e^{-i\delta_{CP}}\sin(\theta_{13}) \\ 0 & 1 & 0 \\ e^{-i\delta_{CP}}\sin(\theta_{13}) & 0 & \cos(\theta_{13}) \end{pmatrix} \]  \hspace{1cm} (5)

\[ C = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{12}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \]  \hspace{1cm} (6)

\( \theta_{12} \) was found by observing solar neutrino oscillations. \( \theta_{23} \) was found through observations of atmospheric neutrinos. The purpose of Double Chooz is to find \( \theta_{13} \). The most scientifically relevant reason for the necessity of knowing \( \theta_{13} \) is to help us understand CP violation (\( \delta_{CP} \)).

## 2 Double Chooz

Double Chooz (pronounced ‘show’) is a neutrino experiment based in Chooz, France. Its two detectors are situated near a pair of nuclear reactors that emit electron antineutrinos (\( \bar{\nu}_e \)). Currently, only one detector is gathering data while the other is being built, but eventually Double Chooz will use both detectors to collect data. The reason two detectors are preferable to one has to do with where the detectors are located. One detector is put next to the reactors so it can collect data of unoscillated antineutrinos. Double Chooz is a disappearance experiment, which means the detectors only see one kind of anti-neutrino. The other detector is put a distance away from the sources (in this case 1 km) so it can collect data after the antineutrinos have oscillated. Rather than attempting to detect a random oscillated flavor of neutrino, Double Chooz is a disappearance experiment, which means the detectors only see to one kind of anti-neutrino. This way, Double Chooz can measure the probability that an electron anti-neutrino will not oscillate using equation 7. The equation is based on the idea that, in a 2 flavor oscillation, the probability that a neutrino will change flavor plus the probability that it’ll stay the same is equal to one.

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2(2\theta_{13}) \sin^2(1.267\Delta m^2L/E) \]  \hspace{1cm} (7)
\[ 1 = P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \]  

\( \Delta m^2 \) was found with a high accuracy from the experiment MINOS[3]. \( L \) is the distance from the source to the detector and is measured in meters. \( E \) is the neutrino energy, measured in MeV. The probability is found by comparing the data collected with predicted data. \( \theta_{13} \), then, ends up being the only variable.

2.1 The Detector

The far detector, pictured in Figure 2, relies on photomultiplier tubes (PMTs) to collect the data. The PMTs convert light into electrical impulses; the more energy released the more light which means the PMTs give off a bigger electrical impulse. The impulse is sent to a computer which reads it as data.

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]  

This reaction is detailed in equation 9. The positron scintillates immediately, which is picked up by the PMTs. The neutron, upon creation, is moving too quickly for a reaction. Once it slows down, it is captured by the Gd. This process gives off a number of gamma rays whose total energy is around 8 MeV. Together, the prompt signal given off by the positron and the delayed signal given off by the gamma rays emitted by the neutron-capture are known as a delayed coincidence. The delayed coincidence enables more accurate data because it’s hard to mimic the delayed signal.

Surrounding the target is the \( \gamma \)-catcher which is filled with liquid scintillator without Gd doping. It is used to ensure all of the gamma rays created in the IBD events are seen by the PMTs. Outside the gamma catcher is the buffer which completes what’s called the inner detector. The buffer is filled with mineral oil to block outside radioactivity which could come from the PMTs or the steel that makes up part of the outer detector. The mineral oil is clear, which allows the PMTs to easily see into the target. The inner veto is the next layer out and is used to prevent background interference. Cosmic ray muons, in addition to other particles, can mimic IBD events. When a muon is seen in the inner veto, everything in the inner detector is ignored for the following microseconds. Beyond the inner veto is 15 cm of steel which shields the inner detector from ambient radiation in the rock surrounding the detector. On top of the detector is the outer veto. The outer veto is made of plastic scintillator strips that are connected to PMTs. The outer veto serves as extra background rejection for cosmic ray muons. The last part of the detector is the calibration glove box. The glove box is connected to a chimney that travels down to the target. Radioactive sources with known energies are dropped down this chimney to calibrate the detector.

2.2 Data Collection

\( \theta_{13} \) is found by running a \( \chi^2 \) fit. There are three main inputs into the fit. The first input is predicted data from a Monte Carlo (MC) simulation. The MC simulation is run to find the predicted anti-neutrino flux. It simulates the Double Chooz experiment, from the reactors to the detectors, and tracks the paths and interactions of each particle. This simulation assumes that the anti-neutrinos do not oscillate. They are
reweighted in an oscillation fit that takes the known variables of equation 7. The MC events are combined with background events that were found by collecting data during a 22 hour period where both reactors were off. There are four types of backgrounds: accidentals, lithium-9, fast neutrons and stopping muons. Together, the expected backgrounds and the MC events make up the predicted data. The second input is a grouping of the systematic uncertainties. This is either in the form of a covariance matrix or pulled parameters.

The third and final input is the collected data from the experiment. When the actual data is collected, there’s a lot of extraneous information embedded. The relevant data pieces are found through a 3 step IBD extraction. The first step is a muon veto. Cosmic ray muons can appear similar to IBD to the PMTs collecting data. The inner veto tags the muons as they pass through and any IBD-like events occurring directly after that are culled. The next step is a data quality cut. The PMTs were found to randomly produce light that could be mistaken for light from the liquid scintillator. Each event is looked at individually and compared to the MC data and lab measurements. The final step is removing delayed coincidences. The delayed coincidence comes from a positron interaction directly followed by a neutron capture of Gadolinium. It’s recognizable by the amount of visible energy given off from each interaction.

2.3 Results

After 227.9 days of collecting data, Double Chooz found a value of \( \sin^2(2\theta_{13}) \) (Equation 10). The histogram in Figure 3, found on the last page, shows the data versus the best fit and what we would expect if there was no oscillation. Each bin of the histogram is .5 MeV, so the y-axis is events per bin while the x-axis is energy. \( \sin^2(2\theta_{13}) \) affects the histogram in the plot at the bottom of the figure by controlling the depth of the dip.

\[
\sin^2(2\theta_{13}) = .109 \pm .030 (\text{stat}) \pm .025 (\text{syst})
\] (10)

3 Public Data Website

My job for this summer was to create a web page that would allow others to see exactly how Double Chooz found the value of \( \theta_{13} \). The webpage will allow the public to see what their tax dollars are working towards, as well as allow other scientists to review our method. The website includes most of the data gathered by Double Chooz, so theoretical scientists can use that to tweak our data to run tests based on our fit. The first step in creating the website was to decide what to use. Initially, there were a series of \( \chi^2 \) fit macros, data files and source files for the data. Only a fitting macro and a plotting macro were needed, so I picked ones that looked at all the data collected by Double Chooz, rather than ones that focused on data from a certain time period. The next step was taking the two macros and breaking them down to their absolute minimum. I merged the two together, which allowed the plot to get number directly from the fit. This allowed the plot to be more accurate and also cut down on the number of files needed for the site. At the beginning, the fit created its own matrices every time it ran. Thinking that unnecessary, I created a separate text file to hold the matrices and let the fit pull from that file. The third step was minimizing the size of the complete package. To run the fit, a number of source files and data files were necessary, but not all the ones provided. I went through and deleted any data files that weren’t used by the macro and any source files that seemed extraneous. When that was finished, it was all grouped together and placed on the website http://www.doublechooz.org/Private/Data_release/DC2ndPubDataRelease.php

4 Future

The website, as of this date, is not open to the public. The Double Chooz analysis group is reviewing the site to make sure it fits their standards. Once they are done, the website will go public. In the future, my webpage can be used for other neutrino experiments looking to allow access to all their data, rather than just a select histogram. The website could be
copied or merely expanded for Double Chooz’s next publication, so that all the data is available to the public.

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References


Figure 3: Histogram of Double Chooz [6]