Double Chooz

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Outline

- Motivation behind studying neutrino oscillations
  - Neutrino Oscillations and Mass Mixing
  - Integrating massive quarks into the Standard Model
- Experiment
  - Detectors
    - Mechanisms behind main detector
    - Motivation for Outer Veto
  - Testing at Nevis
    - Hardware/software tests
Why Study Neutrino Oscillations?

- Its always fun to break down fundamental models
  - In the Standard Model neutrinos are massless, left-handed particles.
  - But current interpretation of Neutrino Oscillations implies that they have nonzero mass
  - Lepton family number conservation violated

- Double Chooz hopes to measure the only yet undetermined mass-mixing angle, $\theta_{13}$.

- This parameter will bring physics one step closer to understanding the implications of lepton oscillation
Oscillation
(two state simplification)

- A neutrino can be described by a wave of either mass states or weak states
  - Different sets of basis vectors for the $\nu$
  - The two are related by a rotation
- so any weak state is a linear combination of mass states
Oscillation
(two state simplification, cont’d)

- neutrino weak state: linear combination of two matter waves.
  - \( f \) determined by mass of wave
  - If equal -> same frequency, no interference
- if masses differ, interference implies oscillation among flavors
Probability of Oscillation

\[ |\nu_\mu\rangle = -\sin(\theta) |\nu_1\rangle + \cos(\theta) |\nu_2\rangle \]
\[ |\nu_e\rangle = \cos(\theta) |\nu_1\rangle + \sin(\theta) |\nu_2\rangle \]

- Start with \( \nu_\mu \) at \( t=0 \)
  \[ |\nu_\mu(t)\rangle = (e^{it(p+\mu m/2E)}) (-\sin(\theta) |\nu_1\rangle + \cos(\theta) |\nu_2\rangle e^{it \Delta m/2E}) \]

- Probability of Osc: \( |<\nu_e |\nu_\mu>|^2 \)
  \[ P(\nu_\mu \rightarrow \nu_e) = |\cos \theta \sin \theta (1-\exp(i\Delta m^2 t/2E_v))|^2 \]
  \[ = \sin^2(2\theta) \sin^2(\Delta m^2 x/E_v) \]
What is $\theta_{13}$?

- In the three state case, the neutrinos are still described by the two sets of basis vectors, which are related by a rotation.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
What is $\theta_{13}$?
(Cont’d)

- This unitary rotation matrix is broken down into three components
- $\theta_{13}$ is the only still unknown mixing angle.
- This part of the unitary rotation matrix will add to our understanding of the mass/flavor mixing

\[
U = \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix} \times \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\]

3-mixing angles

- Solar: $\theta_{12} \sim 33^\circ$
- “Little mixing angle, $\theta_{13}$” $\sin^2 2\theta_{13} < 0.2$ at 90% CL (or $\theta_{13} < 13^\circ$) and $\delta = ?$
- Atmospheric: $\theta_{23} \sim 45^\circ$


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Double Chooz Overview

- Reactor neutrino experiment in Chooz, France that will measure or constrain $\theta_{13}$
- Reactor provides few MeV electron antineutrinos for experiment
- Two main detectors: Near and Far
- Expect to observe a disappearance due to oscillation.

http://irfu.cea.fr/Images/astImg/2260_1.jpg
Detectors

- **The main detector**
  - Gadolinium doped liquid scintillator
    - Charged particles in Scint $\rightarrow \gamma$’s
    - Neutrons interact in Gad $\rightarrow \gamma$’s
  - In scintillator: $\nu_e + p \rightarrow e^+ + n$
    - $e^+ + e^- \rightarrow \gamma + \gamma$ (.5 MeV each)
    - The neutron then interacts with the Gadolinium to produce multiple photons whose energies total to about 8 MeV.

- **Outer Veto**
  - Prevent declaring false signals.
  - Muon interacts producing a neutron.
    - neutron could scatter with a proton, which could react with the scintillator, emulating an electron-positron annihilation
    - The neutron would then be left to interact with the Gadolinium
Outer Veto

- Columbia and collaborators construct the Outer Veto
- four layers of Scintillator strips, each containing a wavelength-shifting fiber
- When a strip is hit by a Muon
  - Photon production in Scintillator
  - Some trapped in wavelength-shifting fiber
    - total internal reflection
  - Detected by PMT
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- testing hardware and software
  - Measured PMT baseline and noise in lightless conditions
    - Baseline - intrinsic to system
    - Noise - characteristic of PMT
- Nevis Outer Veto prototype
  - Expected muon rate and deposited energy
  - Detection and improvements to experiment
System Baseline Measurements

Baseline vs. Time

Baseline vs. HV

Shown for all 64 channels

The mean (max-min)/HV = 0.003 Hits/Volt

Decrease ~ 0.04 ADC hits per hour in 15.5 hours. 0.5 hits -> ~$1/_{70}$ photoelectron
PMT Noise Measurements

Take data when the noise rate in a PMT channel is above the DAC threshold

PMT noise, DAC $< \frac{1}{16}$ pe

- In both cases noise increases .6 hits/second in 90 Volts
- Lower DAC corresponds to higher noise
OV Prototype at Nevis

- Detects Cosmic Muons
- 4 Scintillator strips, 4 pairs of triggers
- Wavelength-shifting fibers coupled to PMT channels
- Define a Muon event with pairs of triggers
  - We consider a trigger to have ‘detected a muon’ if the pixel sees ADC counts > 1 photoelectron
- Trigger modes 0 and 2
Expected Muon Rates

- PDG journal states sea level Muon rate
  - $70 \text{m}^{-2}\text{s}^{-1}\text{str}^{-1}$
- The triggers are $\sim 5\times5$ cm, separated $\sim 4$ cm.
- Solid angle: 2.36 steradians.
- Expect 3000 events in 2 hours, in each trigger counter.
Improvements

- Our first experiment ~1 or 2 photoelectrons, about 100 events in two hours in the nearest trigger

- Potential reasons
  - Optical Crosstalk: when light travels from fibers to PMT channel
    - Losing signal
    - Triggering false muon events (reduce eff)

- Adjustments:
  - Remove spacer and use optical grease
  - Add crosstalk ADC counts (corres to pes) from neighboring channels back into the main pixel while offline
  - Five-fold coincidences
T0: No Spacer with Grease

- 8 photoelectrons, 400 Muons / 2 hours
T2: No Spacer with Grease

- 8 photoelectrons, 1000 Muons / 2 hours
Conclusions and Acknowledgements

- Neutrino oscillations violate SM predictions, making them a compelling field of study.
- Double Chooz will detect or constrain the only yet undetermined mass mixing angle, $\theta_{13}$
- This parameter will bring more information about the nature of neutrino oscillations

Never before have I learned so much so fast, and I thank everyone with whom I worked for passing on knowledge and insight so readily. This REU has been a great experience.
Sources

- Shaevitz, Mike. Reactor Neutrino Experiment and the Hunt for the Little Mixing Angle. Lecture for Yale physics club (Nov 2007)
whitespace
The Weak Force

- Neutrinos only interact via the Weak interaction (and possibly gravity)
- The W boson of the weak force maximally violates parity, and only acts on left handed particles
- If there is a right handed neutrino, or some other flavor that does not interact via weak interactions, it would lead to disappearance that we attribute to 3 state oscillation
How They Acquire Mass

- Separates Dirac from Majorana
- Effective Majorana mass term
- Dirac mass term
- Seesaw mass term (both D and M)
Massive Neutrinos in the SM

- The Standard Model assumes massless neutrinos
- Dirac
  - 4 independent states
    - Must add $\nu_i$ and anti-$\nu_i$
    - If they differ in mass from ordinary $\nu$’s, oscillations into these states can occur
- Majorana
  - Only 2 states
    - Neutrino is its own antiparticle
    - Can transform into one another -> would violate total lepton number conservation
    - Neutrinoless double beta decay
- Both?