Neutrino Oscillations

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Neutrino oscillation experiments may be seeing signs of a new fundamental particle, the sterile neutrino!
Outline

• Neutrinos
  – Properties
  – Sources
• Neutrino Oscillations
• Experiments
  – MiniBooNE
  – MicroBooNE
Neutrinos are fundamental particles that interact via the weak force

- Neutrinos are neutral leptons
- Interact with other particles via the $W^+$, $W^-$ and $Z$ bosons
- Small probability of interaction
- Neutrinos were originally predicted to be mass-less
- Oscillations measurements over the last two decades are evidence that neutrinos have non-zero mass
Neutrinos are produced in nuclear reactions, such as beta decay

- Neutrinos were first hypothesized to explain the missing energy in beta decay.
- The Reines-Cowan Experiment was the first detection of neutrinos via inverse beta decay.
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]
- Anti-neutrinos from a reactor interacted with protons in a tank and produced light.
- Photomultiplier tubes detected the light.
Neutrino Sources in Modern Experiments

- Antineutrinos are produced by beta decay in nuclear reactors

- Particle accelerators produce intense neutrino beams
  - Accelerated protons are smashed into a target
  - Unstable charged pions and kaons are produced
  - Magnetic fields focus the pions and kaons in a beam, where they decay into neutrinos as they travel

![Diagram of neutrino production and detection](image)
Neutrinos come in three flavors

- Electron, muon, and tau neutrinos
- Produced and detected in association with the corresponding charged lepton
- Neutrino interactions conserve lepton flavor number
Neutrinos interact with matter in three different ways

- Anti-electron-neutrino interactions will produce positrons as final state particles
- Lepton Flavor Conservation
- Muon neutrinos produce muons, tau neutrinos produce taus
Neutrino flavor eigenstates can be linear combinations of mass states and vice versa

- The mixing matrix:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- The matrix for the two-neutrino case:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

- Probability of Oscillation:

\[
P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2 \left(1.267 \frac{\Delta m^2 L}{E} \frac{\text{GeV}}{\text{eV}^2 \text{km}}\right).
\]

\[\Delta m^2 = (m_2)^2 - (m_1)^2\]
Neutrinos oscillation experiments look for the disappearance or appearance of neutrinos

- Missing solar neutrinos and atmospheric neutrinos
- Reactor experiments look for disappearance of neutrinos to calculate mixing angles in the mixing matrix
- LSND experiment (Liquid Scintillator Neutrino Detector)
  - Used an accelerator source to confirm neutrino oscillation
  - Saw an excess of electron neutrino events in a muon neutrino beam
  - Results weren’t compatible with the results of other experiments
MiniBooNE detected short baseline $\nu_\mu$ to $\nu_e$ oscillations at Fermilab

- Designed to investigate the LSND results
- Similar L/E as LSND, sensitive to same $\Delta m^2$
- Uses muon neutrinos from the Booster Neutrino Beam at Fermi National Accelerator Laboratory
- Tank of mineral oil and photomultiplier tubes to detect muon and electron neutrino signals
MiniBooNE is a Cherenkov light detector

• Cherenkov radiation is emitted when charged particles pass through medium faster than the phase velocity of light in that medium
• Used Cherenkov light to detect electron and muon neutrino signals

Electron Neutrino  Muon Neutrino  Pi0 (two photons)
MiniBooNE saw an unexpected excess of electron neutrino events

- Sign of the sterile neutrino?

- Muon neutrinos oscillate to a sterile neutrino, which oscillates back to an electron neutrino when detected

- $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ oscillations??

- Are we sure the excess is really not background?

- MiniBooNE can’t easily distinguish electron signals from photon signals
MicroBooNE is designed to investigate the MiniBooNE excess

- MicroBooNE is a Liquid Argon Time Projection Chamber (LArTPC) neutrino detector being built at Fermilab
- Muon and electron neutrinos from the Booster Neutrino Beam weakly interact with the argon
- Ionization charges drift in an applied electric field toward three wire planes
The three wire planes allow us to produce 3-D images of the events

- Photon and electron signals still look similar, but we can now look at the energy deposition of the particles.
- Electrons have a lower $dE/dx$ than photons.
- This will confirm whether or not electrons or photons are causing the MiniBooNE excess.
MicroBooNE will be the largest TPC detector built in the US

- TPC’s are a relatively new technology
- Future experiments will use TPC’s because of their good energy resolution
Summary

• Intense neutrino beams and large scale detectors make it possible to study neutrinos

• Neutrino oscillations are a quantum mechanical effect

• Oscillation experiments may be showing the first signs of the sterile neutrino

• Neutrinos are tiny particles that are providing answers to important questions in fundamental physics

Thanks for listening!