Neutrino Oscillations and the MINOS Experiment

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What's a Neutrino?

- Very small mass
  - \( \lesssim 10^{-6} \) of electron
- No charge
- Interact only via weak force and gravity
- Takes about a light year of lead to stop the average neutrino
Neutrinos Are Very Common

- Most prodigious source: Sun
  - $6.5 \times 10^{10}$ neutrinos/cm$^2$/s at Earth
  - About 1 (!) of these interacts with you a day

- Also produced in detectable quantities by:
  - Cosmic rays
  - Supernovae
  - Radioactive decay in the Earth
  - Nuclear reactors
  - Particle accelerators
Brief History of Neutrinos

• Beta decay in 1930:
  – $n \rightarrow p + e^-$
  – Electron should always have the same energy, but it doesn't!

• Crisis!
  – Bohr: Energy not conserved?
  – Pauli: Maybe there's an invisible particle emitted too?
    • $n \rightarrow p + e^- + \nu$
    • Required to have no charge & nearly no mass
    • Later: 'I have done a terrible thing, I have postulated a particle that cannot be detected'
  – How to test this?
Reines and Cowan

Nuclear explosive

Fireball

30 m

40 m

Buried signal line for triggering release

Back fill

Vacuum pump

Vacuum line

Suspended detector

Vacuum tank

Feathers and foam rubber
Reines and Cowan

- Instead, "Project Poltergeist", which confirmed neutrino in 1956:

- Neutrinos from nuclear reactor make positrons in a water target

\[ p + \nu \rightarrow n + e^+ \]

- First detect 2\( \gamma \) from positron annihilation
- A bit later: \( ^{108}\text{Cd} + n \rightarrow ^{109}\text{Cd} + \gamma \)
Two Kinds of Neutrinos: AGS

• 1950's
  – Pions are a well-known particle, first discovered in cosmic rays
  – Visible decay: $\pi \rightarrow \mu$
  – Clearly also involves a neutrino
  – So $\pi \rightarrow \mu + \nu$
  – Is this the same neutrino, or a different one?
Two Kinds of Neutrinos: AGS

– 1960, Brookhaven
  • Created neutrino beam from decaying pions
    – \( \pi \to \mu + \nu \)
  • Result:
    – \( \nu + n \to p + \mu^- \)
    – \( \nu + n \not\to p + e^- \)
  • This muon neutrino is not the same as the one from beta decay
Three Kinds

– 2000: Tau lepton had been known for some time
  • Must also have an associated neutrino
– DONUT at Fermilab confirms this
  • Same idea as at AGS
  • Beam of neutrinos from $D_s \rightarrow \tau + \nu$
  • Observed: $\nu + n \rightarrow p + \tau^-$
  • More difficult, particularly since the tau lifetime is $3 \times 10^{-13}$ s
Types of Interactions

- So far I've talked about:
  - $\nu_e + n \rightarrow e^- + p^+$
  - $\nu_\mu + n \rightarrow \mu^- + p^+$
  - $\nu_\tau + n \rightarrow \tau^- + p^+$
- Charged current interactions: $W^\pm$

- 1973: Gargamelle bubble chamber
  - $\nu_{e,\mu,\tau} + X \rightarrow \nu_{e,\mu,\tau} + X$
  - Neutral current: $Z^0$

- Picture seems complete, but...
Solar Neutrino Problem

- Fusion in sun produces neutrinos; first detected in 1970 at Homestake mine, SD
  - $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$
    - Rate: ~20/month/100,000 gallons
  - The number was too low by a factor of 3!
- Experiments 1970-2000 observed deficits
  - Solar model wrong? All experiments in error?
• Expect 2 muon neutrinos for each electron neutrino
• Experiments in the 1980's observed closer to 1:1
• Is there a common solution to both problems?
Neutrino Oscillations

• First proposed by Pontecorvo in 1968. Premise:
  – We know neutrinos by their interaction states: \( \nu_e \nu_\mu \nu_\tau \)
  – We could also label them by their masses: \( \nu_1 \nu_2 \nu_3 \)
  – Quantum mechanics does not require a one-to-one correspondence between these!
  – Maybe neutrino interaction states are mixtures of mass states

• For instance, it's a good approximation to say:
  – \( \nu_\mu = \cos \theta \nu_2 + \sin \theta \nu_3 \)
  – \( \nu_\tau = -\sin \theta \nu_2 + \cos \theta \nu_3 \)
  – \( \theta \) is some number which is a constant of nature

• Take a muon neutrino. It's a wave:
Neutrino Oscillations

- $\nu_\mu = \cos \theta \nu_2 + \sin \theta \nu_3$

- Flip it around:

- Now we're back where we started! – Or are we?
Neutrino Oscillations

• Suppose $\nu_2$ is lighter:

  - As the waves interfere, probability of observing $\nu_\tau$ and $\nu_\mu$ change periodically (oscillate)
Neutrino Oscillations

- Oscillation frequency is faster if mass difference is greater
  - Turns out to depend on $\Delta m_{ij}^2 \equiv |m_i^2 - m_j^2|$
  - If masses are the same (maybe zero): no oscillation
- Amplitude controlled by $\theta$
  - No clue of the value except from experiment
Super-Kamiokande

- Found atmospheric neutrino deficit depends on angle!
  - From above: $\nu_\mu : \nu_e \approx 2:1$
  - From below: $\nu_\mu : \nu_e \approx 1:1$
  - Apparently many muon neutrinos change to an unobservable type if they go far enough
SNO

• Designed to detect all solar neutrinos, regardless of type
  – 1000 ton sphere of heavy water
  – $\nu_x + {^2}\text{H} \rightarrow p + n + \nu_x$ (neutral current)

• 2001: Found neutral current interaction rate matched standard solar model
  – All the solar neutrinos were there, but some had changed flavor!
Accelerator Neutrinos

• So far in our story, oscillations have only been observed from sources out of our control (the sun, cosmic rays)
• We'd like to make the neutrinos ourselves and then watch them oscillate, either:
  – $\nu_e$ from a reactor
  – A beam of $\nu_\mu$
• Both are done; MINOS uses the second approach
The Minos Collaboration

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • College de France
Fermilab • Harvard • Holy Cross • IT • Indiana • Iowa State • UC London • Minnesota Duluth • Minnesota Twin Cities
Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas Austin
Tufts • UCL • UFG-Brazil • UNICAMP-Brazil • USP-Brazil • Warsaw • William & Mary • Wisconsin
• MINOS is the second beam neutrino experiment to observe oscillations
  – Beam from Fermilab
  – 2 detectors, one 735 km away
The Idea

- Make a beam of neutrinos
- Observe it once near the source, again far away
- Look for a change
Making a Neutrino Beam

Target Hall

Target

Decay Pipe

Absorber

Muon Monitors

Hadron Monitor

120 GeV protons from Main Injector

10 m 30 m 675 m

π⁺ π⁺ π⁺

ν̄μ μ⁺ μ⁺ ν̄μ

Rock Rock Rock

12 m 18 m 210 m
Near Detector

Tunnel bends out of the page here to filter out everything but neutrinos.
Far Detector

Fermilab

Soudan

735 km

10 km

12 km

2341 FEET BELOW THE SURFACE
689 FEET BELOW SEA LEVEL

Scale
Why Underground?

- Gets us away from cosmic rays
  - Might be confused with beam events
- On the surface, $\sim 100/m^2/s$
- At MINOS, 0.5/s for the entire detector!
- Beam is pulsed – on only 10 $\mu s$ every 2 seconds
  - $\Rightarrow$ $\sim 2$ minutes a year
  - So only $\sim 100$ cosmics/year to worry about
Detector Technology

- Designed to be:
  - Massive (5400 tons)
  - Cheap (per piece)
  - Simple (helps with cheap)

- Alternating planes of steel & plastic scintillator
  - Steel provides mass and supports magnetic field
    - Field allows measurement of muon charge, momentum
  - Scintillator makes light when charged particles pass through
  - Phototubes detect light
Scintillator and Fiber

A scintillator plane

A module

Blue LED lights up scintillator

Fiber

Charged particle
First Far Detector Beam Event
20 March 2005

We've now collected a few thousand
See www.soudan.umn.edu for live MINOS events!

Note the curvature:
this is a $\mu^-$
• As in most neutrino experiments, MINOS can only see one type of neutrino well
  – Muon neutrino: easy to recognize from long clean muon track
  – $\nu + \text{Fe} \rightarrow \mu + X$
• Other two not so easy:
  – Electron neutrino: Possible, but no clear signature in a coarse detector
  – Tau neutrino: Beam is mostly too low energy to produce a tau
• So we look for disappearance
MINOS Observation

- Clear deficit
- Energy dependent – looks like oscillation

- **Done**: MINOS has confirmed oscillations in a controlled environment
- **Current task**: precision measurement of parameters – Capable of ~5-10%
But That's Not All

• Particle experiments milk their data for all it's worth
  – Grad students have lots of opportunities to figure out how to use the detector for things it wasn't designed for!
• I analyze beam events in the surrounding rock that send a muon into the detector, like our first event here:
Rock Muons

- Muon energy only gives a lower bound on $\nu$ energy
- Major components of this study:
  - Making sure the rock simulation is accurate
    - Measured the cavern, drove to Hibbing to examine the core sample, chatted with geologists. Then lots of coding.
    - Finding best method of classifying events to squeeze the most information out of them
Near Detector

- Variety of analyses using ~infinite data

A typical 6-event spill, colored by time
• Atmospheric neutrinos from cosmic rays (like Super-K)

Neutrino from the other side of the Earth
• Look at cosmic rays themselves for various things:
  – Astrophysical point sources or large scale anisotropy
  – Atmospheric effects — can measure the temperature of the stratosphere
– Neutral current disappearance?
– Ordinarily unaffected by oscillations
  • (remember SNO)
– This would imply extra neutrino types, new physics
Electron neutrino appearance?

We assume that in some fractions:

- $\nu_\mu \rightarrow \nu_e$
- $\nu_\mu \rightarrow \nu_\tau$

We know that $\nu_\mu \rightarrow \nu_e$ fraction is small or zero.

Both are hard to measure, but $\nu_e$ is easier.
If $\nu_\mu \rightarrow \nu_e$, there are enough degrees of freedom for a matter/antimatter asymmetry.

- We need this to explain why the universe has large amounts of matter, but not antimatter.

- Exciting topic! Many experiments racing to be the first to observe $\nu_e$ Charged Current.

Short, with typical EM shower profile.
NOvA

• Speaking of electron neutrino appearance...
• Minnesota is part of the NOvA collaboration
  – 15,000 ton detector in northern MN
  – Currently under construction
  – Will start taking data in ~2014

Aug 2009
Summary

• Three kinds of neutrinos have been observed
• Puzzling deficits of neutrinos are well explained by neutrino oscillations, as shown by:
  – SNO (solar)
  – Super-K (atmospheric)
  – MINOS (beam)
  – And others
• The field is moving into the exploration phase
  – Many experiments coming on line
  – Plenty of potential for exciting discoveries
• Come visit! There are daily MINOS tours in the summer
  – Do the historical mine tour while you're there too
  – www.soudan.umn.edu for details
Backup
This represents half of the data taken so far -- new result coming in 2010
3 Neutrino Oscillation

- Expand the two neutrino matrix to a three neutrino matrix (PMNS)
- Replace $\cos(\theta_{ij}) = c_{ij}$ and $\sin(\theta_{ij}) = s_{ij}$, and include phase (CP violation)

\[
U_{PMNS} = \begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
    c_{13} & 0 & e^{-i\delta_{s_{13}}} \\
    0 & 1 & 0 \\
    e^{-i\delta_{s_{13}}} & 0 & c_{13}
\end{pmatrix}
\]

\[
U_{PMNS} = \begin{pmatrix}
    c_{12}c_{13} \\
    -s_{12}c_{23} - c_{12}s_{23}e^{i\delta_{s_{13}}} \\
    s_{12}s_{13} - c_{12}c_{23}e^{i\delta_{s_{13}}}
\end{pmatrix} \begin{pmatrix}
    s_{12}c_{13} \\
    c_{12}c_{23} - s_{12}s_{23}e^{i\delta_{s_{13}}} \\
    -c_{12}s_{23} - s_{12}c_{23}e^{i\delta_{s_{13}}}
\end{pmatrix} \begin{pmatrix}
    e^{-i\delta_{s_{13}}} \\
    s_{23}c_{13} \\
    c_{23}c_{13}
\end{pmatrix}
\]
What Do We Really Do?

• During design and construction:
  – 50% hardware R+D
  – 50% writing/running simulations, documentation, etc. (sitting at a computer)

• Once experiment is running:
  – 95% analyzing data (sitting at a computer)
  – 5% on shift at Fermilab (sitting at a lot of computers)
  – \( \approx 0.1\% \) working on detector — it's very stable!