Physics of Neutrinos
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QMUL, June 21st 2010
Introducing myself:
Introducing the neutrino:
Henri Becquerel, 1896

Accidentally left photographic plates in a dark drawer with some uranium salts...

The plates became “fogged”

The Uranium was emitting something which was interacting with the film...
Radioactivity and momentum conservation

- A* is at rest ($P_{\text{TOTAL}} = 0$)

- A and B must have equal and opposite momenta: 
  \[ p + (-p) = 0 \]

- But, $E^2 = p^2 + m^2$ and the total energy loss is fixed...

- So, there can be only one value of the energy of the escaping particle...
The Beta-decay puzzle

A nucleus decays giving out an electron...

The electron has a range of energies

Energy and momentum aren't conserved!?

Something must be wrong with the picture...?
The “neutrino” hypothesis

What Pauli “saw”:

“What if the missing energy is carried off by an otherwise “invisible” particle...?”

Wolfgang Pauli, 1930
The birth of the neutrino

- It must be **very light**, possibly massless:
  (sometimes, the electron takes all the energy in the decay)

- It must be **electrically neutral**:
  (charge conservation in beta decay)

- It is produced along with an electron:
  (they can’t be made on their own...)

- It must **interact very rarely**:
  (it always escapes the detector without being seen)

Pauli: “I have done a terrible thing. I have invented a particle which cannot be detected...”
Hard but not impossible

It would take $10^{19}$ m (300 light years) of water to absorb a single neutrino.

25 years later

• Frederick Reines and Clyde Cowan
Project Poltergeist

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

\[ p \rightarrow n \quad e^+ \quad \nu_e \]
The biggest nuclear reactor of them all...

10 billion neutrinos from the sun pass through your finger tip every second!
Neutrinos can change chlorine atoms to argon atoms by Inverse Beta Decay

\[ \text{Cl} + \nu_e \rightarrow \text{Ar} + e^- \]

\[ n + \nu_e \rightarrow p + e^- \]

Measure the amount of argon produced in one month...

...find **10 atoms in** $10^{30}$!
Some of our neutrinos are missing...

But expected about 30!

\[ p + p \rightarrow p + n + e + \nu_e + \text{(Energy)} \]

- We “understand” how each nuclear reaction works...
- We can measure how much energy the sun gives out...
- We can accurately predict the number of neutrinos we expect!

\[ N_{\text{neutrinos}} = \frac{\text{Total energy}}{\text{Reaction energy}} \]

Something must be wrong with the neutrinos...
Neutrino Oscillations

nu e waves

Probability of nu e

Earth

Sun
Neutrino Oscillations

\[ P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2 L}{E} \right) \]

- Mass difference $\Delta m^2$
- Neutrino energy $E$
- Distance travelled $L$
- Mixing angle $\theta$
Sudbury Neutrino Observatory

1700 tonnes Inner Shielding $H_2O$

5300 tonnes Outer Shield $H_2O$

12m Diameter Acrylic Vessel

1000 tonnes $D_2O$

Support Structure for 9500 PMTs, 60% coverage

Urylon Liner and Radon Seal

1700 tonnes Inner Shielding $H_2O$
Cherenkov light

- Energetic massive particles can travel faster than light in water
- Photons are emitted as electrons disrupt medium
- We see constructive interference of the wavefronts.
\[ \nu_e + d \Rightarrow p + p + e^- \]

\[ \nu_x + d \Rightarrow p + n + \nu_x \]
SNO Results

Neutrino flux

Standard Solar Model Prediction

$1.0 \text{ (±23\%)}$  

$0.85 \text{ (±9\%)}$

$0.29 \text{ (±6\%)}$

$\frac{\text{CC}}{\text{NC}} = 0.34 \text{ ±0.04}$

http://arxiv.org  nucl-ex/0502021
Where do neutrinos come from?
Cosmic encounters...

• High energy protons from space in all directions

• Hit the atmosphere and produce a “shower” of particles

• This shower includes muons

• These particles decay like beta decay to give...

...neutrinos!
Atmospheric neutrinos

• Muons and electrons can’t just be made or decay on their own...

• Particle “type” must be conserved

• A pion, shower particle produces a muon and a muon neutrino.
  \[ \pi \rightarrow \mu + \bar{\nu}_\mu \]

• The muon decays to a muon neutrino...
  ...and an electron along with an electron neutrino
  \[ \mu \rightarrow \nu_\mu + e + \bar{\nu}_e \]

2 \nu_\mu : \nu_e
Super-Kamiokande
SuperKamiokande
Super-K event display

Sharp edge

Fuzzy ring
Some of our neutrinos are missing....
But only muon neutrinos...
# Fundamental Particles

**The Standard Model**

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Fermions</th>
<th>Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$u$</td>
<td>$\gamma$ photon</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>$Z$ Z boson</td>
</tr>
<tr>
<td></td>
<td>$t$</td>
<td>$W$ W boson</td>
</tr>
<tr>
<td></td>
<td>$d$</td>
<td>$g$ gluon</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td>$V_e$ electron neutrino</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>$V_\mu$ muon neutrino</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_\tau$ tau neutrino</td>
</tr>
</tbody>
</table>

*Yet to be confirmed*  

Source: AAAS
The most powerful neutrino beam in the world.
The T2K Experiment

Target and Horns

ND280 Off-Axis Detector

Super-Kamiokande

Muon Monitor

INGRID On-Axis Detector

Not to scale!
T2K events

First neutrino interaction in ND280 off axis detector
December 19, 2009
T2K events
Summary

- Neutrinos very small, very weakly interacting fundamental particles
- Produced from lots of different sources of radioactive decay
- Detected from nuclear reactors, Sun, Atmosphere, Neutrino beams
- Neutrinos oscillate
- More measurements to make…
Project

• Measure the muon flux and the muon lifetime by detecting cosmic ray muons in the lab.

\[ \mu \rightarrow e + \nu_\mu \]

• What is the cosmic ray neutrino flux?
• How many atmospheric neutrinos pass through you every day?
Neutrinos oscillate
Neutrinos have mass
How heavy are they?
Double Beta Decay

\[ e^- \rightarrow \nu \rightarrow A^* \rightarrow A \rightarrow e^- \nu \]
Double Beta Decay
Neutrino-less Double Beta Decay
Neutrino-less Double Beta Decay

Look for events producing pairs of electrons with this energy.
Neutrinoless double beta decay

- Rate is proportional to neutrino mass.
  
  Mass is very small $\rightarrow$ Rate is very low

- Very long half-life: $\sim 10^{26}$ years

- Look at one nuclei – would have to wait
  
  $\sim 10000000000000000000000000000000$ years!

- Earth is only
  
  $\sim 5000000000$ years old

- Use lots of nuclei.
SNOplus

Liquid scintillator + $^{150}$Nd
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Extra slides
3 neutrinos – 3 mixings

\( V_e \)  \( V_\mu \)  \( V_\tau \)

Mass 1  Mass 2  Mass 3