Overview

- Pauli postulates Neutrino
- Discovery of neutrino flavours
  - Electron, muon and tau neutrinos
- Neutrino Interactions
  - Cross sections
- Neutrino mass
  - Direct measurement
- Neutrino oscillations
  - Lepton flavour violation
  - Formalism
- Solar neutrinos
  - Homestake, Super-K and SNO
- Atmospheric neutrinos
  - Super-K
- Discovery of Neutrino Mass
  - Neutrino oscillations
- Cosmology
Particle Physics in 1930

Only 3 known fundamental particles: e-, p, γ
Continuous energy spectrum of e- in beta decay

Pauli postulates Neutrino

Dear radioactive Ladies and Gentleman

"... desperate remedy to save ... the law of conservation of energy"
"... that there could exist ... neutrons"
"in beta decay a neutron is emitted in addition to the electron"

1934 name - “neutrino” coined by Fermi
1932 neutron discovered by Chadwick
Neutrino Interactions

Neutrinos

point-like leptons
do not interact strongly, no colour charge
charge \( Q = 0 \) \( \rightarrow \) no electromagnetic interactions
Only weak interactions by coupling to \( W^\pm \) and \( Z^0 \)
Expect very small detection rates

"I have done a terrible thing. I have postulated a particle that cannot be detected." Pauli

Inverse Beta Decay

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

Cross section

\[ \sigma(\bar{\nu}_e + p \rightarrow n + e^+) \approx 5 \cdot 10^{-44} \left( \frac{E_{\bar{\nu}}}{\text{MeV}} \right)^2 \text{cm}^2 \]

Mean Free Path

60 light years of water for 1 MeV anti-neutrino

\[ \lambda = \frac{1}{n \sigma} \approx 6 \cdot 10^{19} \text{cm} \approx 60 \text{ light years} \quad n = Z \frac{N_A}{A} = 3.34 \cdot 10^{23} \text{cm}^{-3} \]

1 \( \nu \) in \( 10^{11} \) interacts when crossing the earth
Require huge rates as neutrino sources
**Discovery of Neutrinos**

**Electron Neutrino** $\nu_e$ discovered 1956 by Reines and Cowan
- Anti-neutrino source
- Nuclear reactor --- anti-$\nu$ flux $6 \cdot 10^{20}$ s$^{-1}$
- Target and Detector --- 400 l liquid scintillator
  - Water and Cadmium Chloride
- Detection of anti-neutrino $\bar{\nu}_e + p \rightarrow n + e^+$
  - $e^+e^- \rightarrow \gamma\gamma$
  - $nCd \rightarrow Cd^+ \rightarrow \gamma Cd$
- Delayed coincidences only produced by signal

**Muon Neutrino** $\nu_\mu$ 1962 at Brookhaven by Ledermann, Steinberger, Schwartz
- Pion beam
- Iron absorber --- only muons survive
  - $\pi$-beam $\pi^+ \rightarrow \mu^+\nu_\mu$  
  - $\pi^- \rightarrow \mu^-\bar{\nu}_\mu$
  - observe $\nu_\mu + n \rightarrow \mu^- + p$  
  - $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - don't see $\nu_\mu + n \rightarrow e^- + p$  
  - $\bar{\nu}_\mu + p \rightarrow e^+ + n$

$\Rightarrow$ $\nu_\mu$ and $\nu_e$ are different

**Tau Neutrino** $\nu_\tau$ 2000 at Fermilab - Donut
- p on tungsten target produce $D_s$ mesons
  - $D_s^+ \rightarrow \tau^+ + \nu_\tau$
  - $\nu_\tau + N \rightarrow \tau^- + X$
  - $\tau^- \rightarrow \mu^- + \nu_\tau + \bar{\nu}_\mu$
Neutrino Physics

Neutrino Sources
- Natural radioactivity - e.g. rocks
- Cosmic rays hitting the atmosphere
- Nuclear reactors
- Particle accelerators
- Sun - nuclear fusion reactor
  \[ 4p \rightarrow ^4He + 2e^+ + 2\nu_e + 26.7\text{ MeV} \]
- Flux on earth \( \sim 10^{11}\text{ cm}^{-2}\text{s}^{-1} \)
  100 billions/sec through your finger nail

Neutrino Mass
- No apparent “reason” for neutrino to be massless
  all other fermions have mass

Direct mass measurements
- Beta decay energy spectrum
  \[ \frac{d\Gamma}{dE} = \frac{G_F^2}{2\pi^3} (E_0 - E_e)^2 E_e^2 \]
  \[ \sqrt{\frac{d\Gamma}{dE}} \frac{1}{E_e^2} \propto E_0 - E_e \]

  Endpoint modified by resolution
  and non-zero \( \nu_e \) mass

  Tritium Beta Decay Mass \( m(\nu_e) < 3\text{ eV} \)

Neutrino Oscillations
- No apparent “reason” for neutrinos not to oscillate
  into each other
  \( \nu_e \nu_x \nu_x \nu_x \)

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Neutrino Oscillations

Lepton flavour conservation

\[ L_e, L_\mu, L_\tau \] are conserved separately

Neutrinos with mass can mix - weak eigenstates are linear superpositions of mass eigenstates

\[ \Rightarrow L_e, L_\mu, L_\tau \] not absolutely conserved

\[ L_e, L_\mu, L_\tau \] Violation too small to observe BF < 10^{-40}

2 Neutrino flavours

Easy to understand, can be expanded to 3 generations

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

Time evolution

\[ \nu_1(t) = \nu_1(0) \exp(-iE_1 t) \]
\[ \nu_2(t) = \nu_2(0) \exp(-iE_2 t) \]

Intensity \( I(t) \) for initial \( \nu_e \) beam

\[ I_{\nu_e}(t) = I_{\nu_e}(0) \left( \cos^2 \theta + \sin^2 \theta \right)^2 - 4 \sin^2 \theta \cos^2 \theta \sin^2 \left( \frac{E_2 - E_1}{2} t \right) \]

Neutrino energy \( E \) and mass difference \( \Delta m_{12}^2 \)

\[ E_i^2 = p_i^2 + m_i^2 \quad E_i >> m_i \quad \Delta m_{12}^2 \equiv m_2^2 - m_1^2 \]

\[ \Rightarrow E_i \approx p_i + \frac{m_i^2}{2p_i} \quad \Rightarrow \Delta E \equiv E_2 - E_1 \approx \Delta m_{12}^2 / 2E \]

Neutrino Oscillation Probabilities

\[
P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2 \theta \sin^2 \left( \frac{1.27 \Delta m_{12}^2 [eV] L [m]}{E [MeV]} \right)
\]

\[
P(\nu_e \rightarrow \nu_\mu) = \sin^2 2 \theta \sin^2 \left( \frac{1.27 \Delta m_{12}^2 [eV] L [m]}{E [MeV]} \right)
\]

Distance from source \( L [m], E [MeV] \) and \( \Delta m_{12}^2 [eV^2] \)
Solar Neutrinos

**Standard Solar Model (SSM)**

Predicts rates and solar neutrino energy spectra

- pp flux below 0.42 MeV
- $^8$B $\nu_e$ up to 14 MeV

**pp cycle**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow$</td>
<td>$^2\text{H} + e^+ + \nu_e$</td>
</tr>
<tr>
<td>$^2\text{H} + p$</td>
<td>$^3\text{He} + \gamma$</td>
</tr>
<tr>
<td>$^3\text{He} + ^3\text{He}$</td>
<td>$^4\text{He} + 2p$ 83%</td>
</tr>
<tr>
<td>$^3\text{He} + ^4\text{He}$</td>
<td>$^7\text{Be} + \gamma$ 13%</td>
</tr>
<tr>
<td>$e^- + ^7\text{Be}$</td>
<td>$^7\text{Li} + \nu_e$</td>
</tr>
<tr>
<td>$^7\text{Li} + p$</td>
<td>$^{24}\text{He}$</td>
</tr>
<tr>
<td>$p + ^7\text{Be}$</td>
<td>$^8\text{B} + \gamma$ 0.02%</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>$^8\text{Be}^* + e^+ + \nu_e$</td>
</tr>
<tr>
<td>$^8\text{Be}^*$</td>
<td>$^{24}\text{He}$</td>
</tr>
</tbody>
</table>

**Homestake Experiment**

First observed solar neutrinos in 1970s

100,000 gallons of cleaning fluid $C_2Cl_4$

**Measurement**

$\nu_e + ^37\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$

0.5 Ar atoms/day

$2.56 \pm 0.23$ SNU

**SSM prediction**

1.5 Ar atoms/day

$7.7 \pm 1.3$ SNU

**Puzzle - What is wrong?**

1 SNU = 1 interaction

Experiment, SSM, Neutrinos $10^{36}$ target atoms/sec
**Solar Neutrinos II**

**Super-Kamiokande**

50,000 tons of water, 11,000 phototubes
underground inside a mine in Japan, started 1997

$\nu_e$ Detection

Elastic scattering

$\nu_e + e^- \rightarrow \nu_e + e^-$

Directional sensitivity

**Measurements**

$(0.465 \pm 0.005 + 0.016 - 0.015) \times SSM$

$\nu_e$ definitely from sun

Signal from centre of sun

**Puzzle – What is wrong?**

Homestake experiment confirmed

Experiment, SSM, Neutrinos
SNO --- Sudbury Neutrino Observatory

1000 tons of heavy water (D$_2$O)
10,000 photo multipliers tubes

Sensitivity

SNO is able to measure $\nu_e$ - Charged Current
but also $\nu_\mu$ and $\nu_\tau$ ($\nu_{i=e,\mu,\tau}$) - Neutral Current

Charged current (CC) $\nu_e + D \rightarrow p + p + e^-$
Elastic scattering (ES) $\nu_i + e^- \rightarrow \nu_i + e^-$
Neutral current (NC) $\nu_i + D \rightarrow n + p + \nu_i$

Measurements

2003 results

$Flux_{CC} = 1.59^{+0.10}_{-0.11} \times 10^{-6} \text{ cm}^{-2} \text{s}^{-1}$
$Flux_{ES} = 2.21^{+0.33}_{-0.28} \times 10^{-6} \text{ cm}^{-2} \text{s}^{-1}$
$Flux_{NC} = 5.21 \pm 0.47 \times 10^{-6} \text{ cm}^{-2} \text{s}^{-1}$

$CC / NC = 0.306 \pm 0.036$

31% of solar $\nu$'s arrive as $\nu_e$ at earth
100% of solar $\nu$'s detected if $\nu_\mu$ and $\nu_\tau$ are included

Puzzle - What is wrong?

Experiment, SSM, Neutrinos

Neutrino Oscillations

$\nu_e$ change to $\nu_\mu$ in flight

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**Atmospheric Neutrinos**

**Cosmic Rays**
Protons hit nuclei in upper part of atmosphere
Producing chain of particles
copious source of neutrinos

**Main decay sequence**
\[ \pi^+ \rightarrow \mu^+ \nu_\mu \quad \text{and} \quad \pi^- \rightarrow \mu^- \bar{\nu}_\mu \]
\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \quad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \]

Expect 2 \( \nu_\mu \) for each \( \nu_e \)

~1990 1\textsuperscript{st} indications for “too few \( \nu_\mu \)"

**Super-Kamiokande**
Can discriminate \( \nu_\mu \) from \( \nu_e \)

\[ \nu_\mu + N \rightarrow \mu^- + X \quad \nu_e + N \rightarrow e^- + X \]

Recoil muon produces clean ring
Recoil e- produces fuzzy ring

\[ \nu_\mu + N \rightarrow \mu^- + X \quad \nu_e + N \rightarrow e^- + X \]
Atmospheric Neutrinos II

Measurements
- 1998 Super-Kamiokande
- Observe significant deficit of $\nu_\mu$ and agreement for $\nu_e$

Neutrino Disappearance
- $\nu_\mu$ traversing the earth i.e. arriving at the detector from below disappear

Neutrino Oscillations
- Atmospheric neutrinos $\nu_\mu$ change to $\nu_\tau$ in flight
- First Evidence for Neutrino Oscillations

Nuclear and Particle Physics Franz Muheim
**Discovery of Neutrino Mass**

**Atmospheric Neutrino Oscillations**
- Atmospheric $\nu_\mu$ change into $\nu_\tau$
- Oscillation probability
- Fit data for best values of mass difference $\Delta m_{23}^2$ and mixing angle $\theta_{\mu\tau}$
- Find $\theta_{\mu\tau} \approx 45^0$ and $\Delta m_{23}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2$

→ **Neutrinos have Mass**

**Solar Neutrino Oscillations**
- Super-Kamiokande, SNO
- Kamland - reactor anti-$\nu_e$
- Find $\theta_{e\mu} \approx 33^0$ and $\Delta m_{12}^2 \approx 8.0 \times 10^{-5} \text{ eV}^2$

**Neutrino mass**
- Minimum $m_\nu \sim 0.05 \text{ eV}$
- 2 scenarios

**Cosmology**
- Big Bang large nr. of neutrinos
- Neutrinos are hot dark matter candidates

**Supernova 1987A**
- Kamiokande and IMB
- Observed $\sim 10$ neutrinos