$\tau$ neutrino detection

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Outline

- Standard Model and History
- Detection of neutrinos (specifically $\nu_\tau$)
- Direct Observation of NU Tau (DONUT)
- Oscillation Project with Emulsion-tRacking Apparatus (OPERA)
The Standard Model of Particle Physics

Three Generations of Matter (Fermions)

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
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<tbody>
<tr>
<td>Mass</td>
<td>2.4 MeV</td>
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<td>Charge</td>
<td>$\frac{2}{3}$</td>
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<tr>
<td>Spin</td>
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<td>$\frac{1}{2}$</td>
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<tr>
<td>Name</td>
<td>u (up)</td>
<td>c (charm)</td>
<td>t (top)</td>
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<td></td>
<td>4.8 MeV</td>
<td>104 MeV</td>
<td>4.2 GeV</td>
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<td>$-\frac{1}{3}$</td>
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<td>$\frac{1}{2}$</td>
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<tr>
<td>Quarks</td>
<td>d (down)</td>
<td>s (strange)</td>
<td>b (bottom)</td>
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<tr>
<td></td>
<td>&lt;2.2 eV</td>
<td>&lt;0.17 MeV</td>
<td>&lt;15.5 MeV</td>
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<tr>
<td>Leptons</td>
<td>e (electron)</td>
<td>$\nu_e$ (electron neutrino)</td>
<td>$\nu_\mu$ (muon neutrino)</td>
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<td></td>
<td>0.511 MeV</td>
<td>&lt;0.17 MeV</td>
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<tr>
<td></td>
<td>electron</td>
<td>muon</td>
<td>tau</td>
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<td>1898- electron</td>
<td>1937-muon</td>
<td>1956-electron neutrino</td>
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<td>1974-charm quark</td>
<td>1975-tau lepton</td>
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<td>1977-bottom quark</td>
<td>1995-top quark</td>
<td>2000-tau neutrino</td>
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Bosons (Forces)

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<tr>
<td>Spin</td>
<td>1</td>
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<tr>
<td>Name</td>
<td>$Z^0$ (weak force)</td>
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<td></td>
<td>1898- electron</td>
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<tr>
<td></td>
<td>1937-muon</td>
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Tau Neutrino was the last standard model fermion to be directly observed.
History

Discovery of electron neutrino: 1956

The million-dollar particle

- Reactor neutrinos: $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma + \gamma$ (0.5 MeV each)
- $n + ^{108}$Cd $\rightarrow ^{109}$Cd* $\rightarrow ^{109}$Cd + $\gamma$ (delayed)

Reines-Cowan: Nobel prize 1995
Discoveries of $\nu_\mu$ and $\nu_\tau$

Muon neutrino: an unexpected discovery (1962)
- Neutrinos from pion decay: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- $\bar{\nu}_\mu + N \rightarrow N' + \mu^+$
- Always a muon, never an electron/positron

Steinberger-Schwartz-Lederman: Nobel prize 1988

Tau neutrino: expected, but hard to identify (2000)
DONUT experiment at Fermilab: $\nu_\tau + N \rightarrow \tau + N'$
Evidences before discovery

- The Discovery of $\tau$ in 1975 along with the proof in 1962 that $\nu_\mu$ was distinguished from the $\nu_e$, implied the existence of unique $\tau$ neutrino.

- Constraint on total number of neutrinos (to be 3) by Big Bang nucleosynthesis.

- Precise measurement of partial decay width of Z at LEP, predicts 3 light neutrinos.
Neutrino interactions

- Neutrino interactions can be reduced to two categories:
  1. Neutral Current (Z)
  2. Charged Current (+/-W)

- The purpose of the DONuT experiment is to study CC events:
  \[ \nu_{\tau} + N \rightarrow \tau^- + X \]
  \[ \bar{\nu}_{\tau} + N \rightarrow \tau^+ + X \]

- However during data taking DONuT was recording interactions of all flavors of neutrinos.
  1. CC event
     \[ \nu_{l} + N \rightarrow l^- + X \]
  2. NC event
     \[ \nu_{l} + N \rightarrow \nu_{l} + X \]

- Background: Charm production in NC event of \( \nu_\mu \) and \( \nu_e \)
  \[ \nu_{l} + N \rightarrow l^- + C^\pm + X \]
Neutrino Interactions

\[ \nu_\mu \text{ CC} \rightarrow \text{penetrating muon} \rightarrow \text{long event} \]

CC \( \nu_\mu \) interaction to a muon, giving long track of muon.

\[ \nu_e \text{ CC} \rightarrow \text{showering electron} \rightarrow \text{short event} \]

CC \( \nu_e \) interaction to an electron, producing showering event.

\[ \nu \text{ NC} \rightarrow \text{no muon, hadrons} \rightarrow \text{short event} \]

NC event any neutrino can undergo, only multiple hadron products

\[ \nu_\tau \text{ CC} \rightarrow 18\% \text{ BF to a penetrating muon} \rightarrow \text{long event} \]

CC \( \nu_\tau \) bit more difficult due to \( \tau \) lifetime

\[ \nu_\tau \text{ CC} \rightarrow 18\% \text{ BF to an electron} \rightarrow \text{short event} \]
1. 800 GeV proton beam (Tevatron) stopped in beam dump (block of tungsten).
2. Produces $D_s$ (meson) decays to $\bar{\nu}_\tau$ and $\tau$
3. $\tau$ then decays to tau neutrino
4. Which is detected in emulsion target
800 GeV proton beam from TeVatron collide with block of tungsten.

8 \times 10^{12} \text{ protons per 20 second spill}

In the Dump D_s (along with other charm particles) is produced.

Neutrinos from decay of charmed particle are called prompt neutrinos.
Neutrinos from decay of \( \pi^\pm \) and \( K^\pm \) are called Non prompt neutrinos.
95\% of neutrino flux are \( \nu_e (37\%) \) and \( \nu_\mu (58\%) \) and rest is \( \nu_\tau \)
93\% of \( \nu_e \) are prompt, substantial \( \nu_\mu \) are both prompt and non prompt and almost \( \nu_\tau \) all are prompt
Neutrino Beam Energy

- The calculated (PYTHIA output) neutrino energy spectra of all neutrinos that interacted in DONuT

- The average neutrino energy was 53 GeV

DONuT Detector

DONUT Detector

Identification of muons coming from tau decay

Calorimeter determines energy of decay products

Drift chambers record decay particle tracks

Magnet spreads tracks of charged particles

Emulsion target with planes of scintillation fibers

Steel shield to block particles other than neutrinos

DONUT Detector for direct observation of tau neutrinos ($\nu_\tau$)
DONuT Target

- DONuT scientists had to overcome two difficulties:
  1. High resolution: $\tau$ has short lifetime $\sim 239 \times 10^{-15}$s (PDG)
  2. Tau-neutrino is extremely non-interacting

**Solution: EMULSION**
- Spatial Resolution $\sim 1\mu$m
- Extremely sensitive and also continuously sensitive
- Target and detector are not separate.
- To improve target densities emulsions are layered on sheets of metal.
- Number of grains developed per unit track length gives rate of energy loss

![Graph showing the ratio $Y_{\tau}/Y_\mu$ against $E_\nu$ (GeV)]
DONuT Target

DONUT Target Station

- Emulsion-Target
- 50x50x6 cm$^3$
- Aluminium support frame
- Masses of these module range from 56 kg - 100 kg
An appearance experiment to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in CNGS beam

OPERA is a long baseline experiment located at the Gran Sasso laboratory.

The Detector design is based on massive lead/nuclear emulsion target

The Concept of emulsion detector in OPERA is same as DONuT, one difference in the nature of passive material. In OPERA there are lead plates but in DONuT there are iron plates

The most stringent constraint comes from SuperK which yeilds the following 90% C.L.

$$\Delta m^2 \sim (2-6) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta \sim 0.8 - 1$$
OPERA Requirements

- The energy of $\nu_\mu$ must be over the $\pi$ production threshold.
- The distance from the $\nu_\mu$ production point to the detector (baseline) must be long enough to allow a reasonable fraction of neutrinos to oscillate to a different flavour.
- The beam intensity must be high enough to provide a reasonable number of events.
- The detector must have enough mass to provide a reasonable number of events.
- The detector must have a capability to detect short-lived leptons, that is high spatial resolution.
Detecting $\nu$ tau @ OPERA
Conclusion

- The results from DONuT in July 2000, confirmed the existence of most suspected nu tau.
- Finding $\tau$ decay in DONuT was made possible by state-of-the-art digital technology with precise nuclear emulsion.
- The OPERA detector received CNGS nu beam for a brief period in 2006 and obtained first event in 2007.

THANK YOU !!!