History

1896 Discovery of Radio activity

1911 Continuos spectrum of e^- in β-decay measured

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^-$$

spin 0   spin 1   spin $\frac{1}{2}$

⇒ conservation laws of energy & momentum violated?

⇒ Big confusion among physicists at that time

even Bohr believed that conservation laws could be violated.

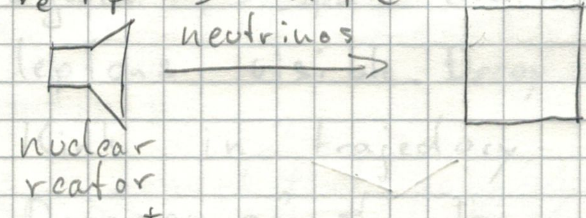
1930 New particle postulated by Pauli to solve this problem

1933 Fermi names the new particle Neutrino

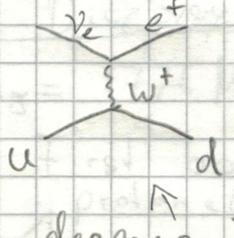
⇒ Fermi's theory of β-decay: neutrino assumed to be massless and chargeless

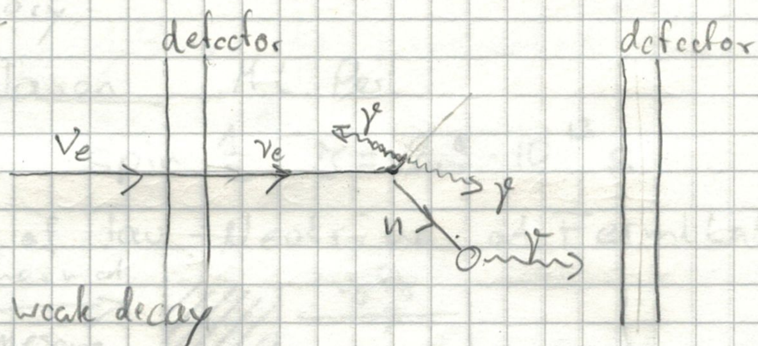
Cowan and Reines neutrino experiment 1956

$$\nu_e + p \rightarrow n + e^+$$



tank with water containing cadmium chloride placed between large liquid scintillation detectors





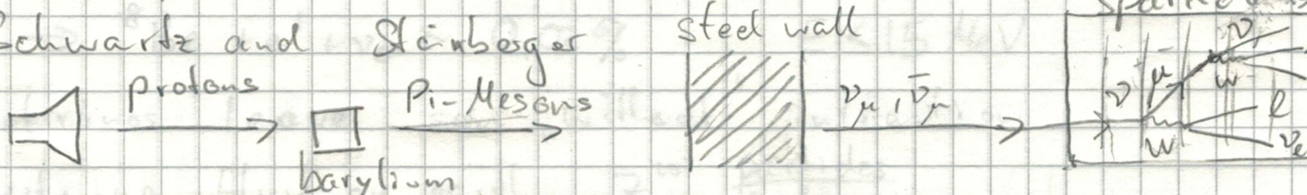
- ν_e decays into e^+ via weak decay
- e^+ slowed down in water and annihilated producing two gammas
- the neutron is also slowed down and eventually captured by cadmium nucleus ⇒ one gamma (reaches detector about a microsecond after the two gammas from positron annihilation)

Muon neutrino

1936 Muon discovered in Cosmic Radiation

$m_\mu = 105\,GeV$ $q = -e$ spin $\frac{1}{2}$ $\tau = 2{,}2\,\mu s$

1962 Discovery of the muon neutrino by Ledermann Schwartz and Steinberger

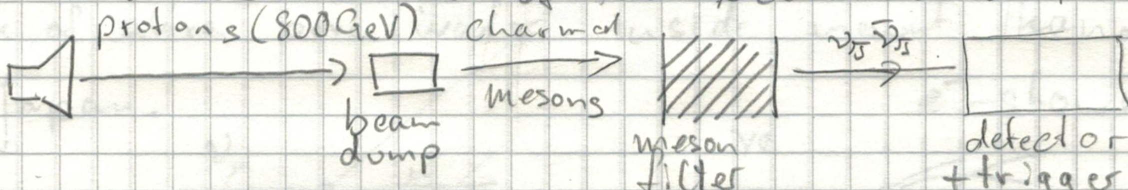


- Protons are shot onto a barylium target.
- Pi Mesons are created which decay mainly into $\mu^- + \bar{\nu}_\mu$ and $\mu^+ + \nu_\mu$. Decay into electrons is surpressed by heilicity.
- Muons are filtered out by steel wall
- Neutrinos eventually decay into muons in spark chambes and then muons can decay into neutrinos again. ⇒ Spark chambes makes trajectories of leptons visible. Decay of muon can be seen as kink in trajectory.

1975 Discovery of the Tauon M.L. Perl

$m_\tau = 1776\,MeV$ $q = -e$ spin $\frac{1}{2}$ $\tau = 2{,}9 \cdot 10^{-13}\,s$

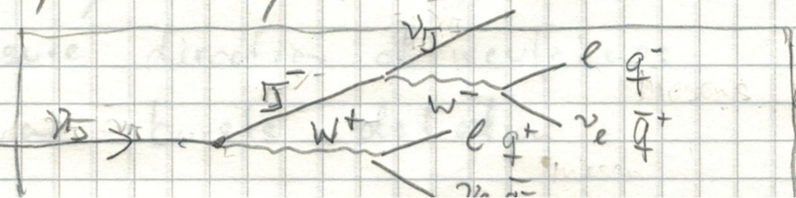
2000 First observation of Tau-Neutrino at FermiLab



→ protons get shot on beam dump (cooled block of metal because protons are very energetic)

→ Charmed mesons eg. $|c\bar{s}\rangle$ are created which decay mainly into Tauons (see above)

therfore



Solar Neutrinos

Neutrinos get produced in the sun by nuclear fusion

$p + p \rightarrow d + e^+ + \nu_e$ ~ 86% solar neutrinos $E < 0{,}4$ MeV

$^7Be + e^- \rightarrow {}^7Li + \nu_e$ ~ 14% $E < 0{,}8$ MeV

$^8B \rightarrow {}^8Be + e^+ + \nu_e$ ~ 0,02% $E < 15$ MeV

→ Neutrinos leave sun „without" interaction

Neutrino flux on earth 7^{10} $\frac{\text{particles}}{cm^2 \cdot s}$

1969 R Davis found that there are less neutrinos coming from the sun than there should be

⇒ Homestake experiment: tank filled with C_2Cl_4 placed about 1,5 km under the surface (so cosmic radiation doesn't effect measurements)

$^{37}_{17}Cl + \nu_e \rightarrow {}^{37}_{18}Ar + e^-$ | detects neutrinos from boron 8 prod.

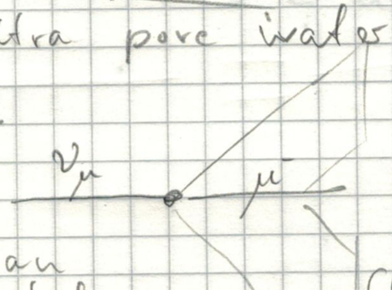
→ Radioactive Argon summons in tank

→ Measurement of radioactivity gives number of neutrino reactions

→ Davis found that only 1/3 of the predicted neutrino flux from sun is measured.

Super Kamiokande

Tank of ultra pure water inside mount Ikenoyama in Japan.



→ Detector can distinguish between ν_μ and ν_e

On the walls of the tank photomultipliers are placed

⇒ Measures ν_μ ν_e flux from sun → $\frac{2}{3}$ flux expected

⇒ can measure direction of neutrinos

Supernova bursts detection

SNO

Tank filled with heavy water also placed deep under the surface of earth.

Neutrinos react with heavy water via neutral currents.

⇒ Cherenkov radiation of scattered particles

⇒ Measures flux of all neutrino flavours from sun

In agreement with prediction!

Neutrino oscillations

flavour eigenstates ν_α $\alpha = e, \mu, \tau$

mass eigenstates ν_i $i = 1, 2, 3$

$$\Rightarrow |\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \Rightarrow |\nu_i\rangle = \sum_\alpha U_{i\alpha}^* |\nu_\alpha\rangle$$

⇒ time evolution $|\Psi(t)\rangle = e^{-i\frac{Ht}{\hbar}} |\Psi(0)\rangle$

⇒ probability of finding a neutrino in some other flavour eigenstate after time t:

$$|\langle \nu_\beta(t) | \nu_\alpha(0)\rangle|^2$$

$$\Rightarrow \langle \nu_\beta(t) | \nu_\alpha(0)\rangle = \langle \nu_\beta(0) | e^{-i\frac{Ht}{\hbar}} | \nu_\alpha(0)\rangle$$

$$= \sum_{ij} U_{i\beta}^* U_{\alpha j} e^{-i(E_j t/\hbar - p_j x)} \langle \nu_i | \nu_j \rangle$$

$$= \sum_i U_{i\beta}^* U_{\alpha i} e^{-i(\frac{E_i t}{\hbar} - p_i x)}$$