Historical Introduction

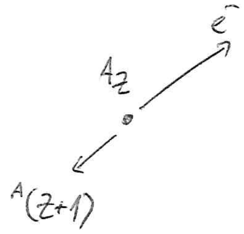
1896 Discovery of radioactivity by Bequerel

~1900 Classification of three kinds of radiation by Rutherford / Villard

(α) $^{A}Z \longrightarrow {}^{(A-4)}(Z-2) + {}^{4}He^{++}$

(β) $^{A}Z \longrightarrow {}^{A}(Z \pm 1) + e^{\mp}$

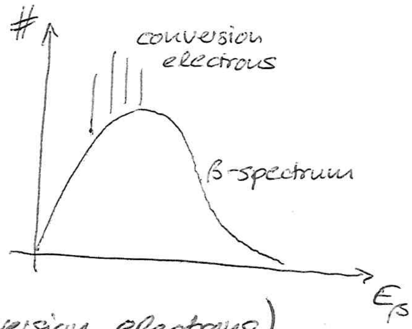
(γ) $^{A}Z^{*} \longrightarrow {}^{A}Z + \gamma$



→ two-body decays

→ mono-energetic radiation

1911 Rutherford model of the atom:
nucleus of protons + electron shell



1914 Chadwick & Geiger:
Continuous β spectrum (+ lines from conversion electrons)

→ energy conservation violated!

In addition: Angular momentum / spin conservation,

e.g. decay of free neutron

$$n \longrightarrow p + e^-$$

$$s = \tfrac{\hbar}{2} \qquad \underbrace{s = \tfrac{\hbar}{2} \quad s = \tfrac{\hbar}{2}}$$

$$\Sigma s = 0, \pm 1 \quad ↯ \longrightarrow \text{violation!}$$

Solution: Postulate of the neutrino

1930 Pauli → 3^{rd} particle in β-decay ("neutron")

properties:
- low mass: $m_\nu \lesssim m_e$
- half spin: $s = \hbar/2$ (Fermion)
- no electric charge → not seen in experiments

1932 Discovery of neutron "n" by Chadwick

→ ν redubbed "neutrino" by Fermi

1934 <u>Fermi's theory</u> of β decay as "contact / 4-particle" interaction

Fermi's Golden Rule: $$\lambda_{if} = \frac{2\pi}{\hbar} \, | M_{if} |^2 \, \rho_f$$

- λ_{if}: transition probability
- M_{if}: matrix element of interaction (nuclear transition)
- ρ_f: phase-space density of final state

→ correctly predicts shape for allowed transitions / decays

→ <u>weak</u> <u>interaction</u> of neutrinos with electrons / nuclei

Predicted <u>cross-sections</u> <u>very</u> <u>low</u>:

e.g. at $E = 1\,\mathrm{MeV}$: Compton scattering: $\sigma_{\gamma e} \sim 10^{-28}\,m^2$

Elastic νe scattering: $\sigma_{\nu e} \sim 10^{-49}\,m^2$

Direct detection of the "free neutrino"

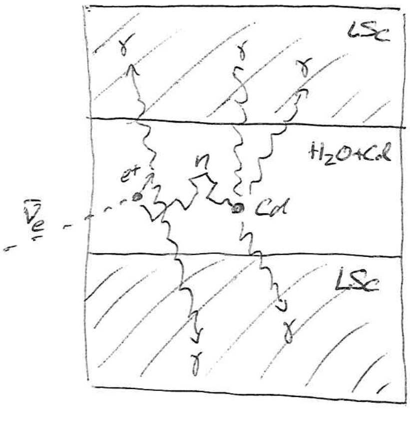
- 1st idea: nuclear explosion + close-by detector
- later on: β-decays of neutron-rich isotopes from fission

  → detector placed close to nuclear reactor

$$\mathring{N}(\bar{\nu}_e) \approx 10^{20}\,s^{-1} \cdot \frac{P_{th}}{GW}$$

1956 Savannah River experiment by Reines & Cowan

Neutrino detector



- target:
  water tank (200l)
  doped with cadmium
- detection reaction:
  inverse beta decay

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

e^+ ↓ (instantaneous) $e^+e^- \to \gamma\gamma$

n ↓ $n\,Cd \xrightarrow{Cd^*} \gamma\gamma\gamma$ (delayed $O(10\mu s)$)

→ delayed coincidence tag!

→ discrimination of single-event backgrounds (γ's, n's, cosmic events)

- challenge: very low detection rate (order events per day)

→ background from reactors (γ, n) and cosmic muon spallation

→ result: increase in rate during reactor-on periods, corresponding to predicted cross section of IBD

Neutrino and antineutrino

(β^-) $n \rightarrow p + e^- + \bar{\nu}_e$

(β^+) $p \rightarrow n + e^+ + \nu_e$

are these different particles?

1955-1960 Experiment @ Brookhaven research reactor by R. Davis

Reactor: n-rich isotopes from fission → $\bar{\nu}_e$ source

Detector: Tank holding 6 tons of tetrachlorethylene C_2Cl_4

- Reaction: $\nu_e + {}^{37}_{17}Cl \longrightarrow {}^{37}_{18}Ar + e^-$

  ↳ only for (electron) neutrinos!

- Interaction rate: determined by ^{37}Ar re-decay (see below)

→ result: reaction rate < 10% of expectation for $\nu = \bar{\nu}$

More than one neutrino flavor?

- $n \longrightarrow p + e^- + \bar{\nu}_e$
- $\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$

are these different particles?

Important hint:

μ decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$, not $\mu^- \rightarrow e^- + \gamma$

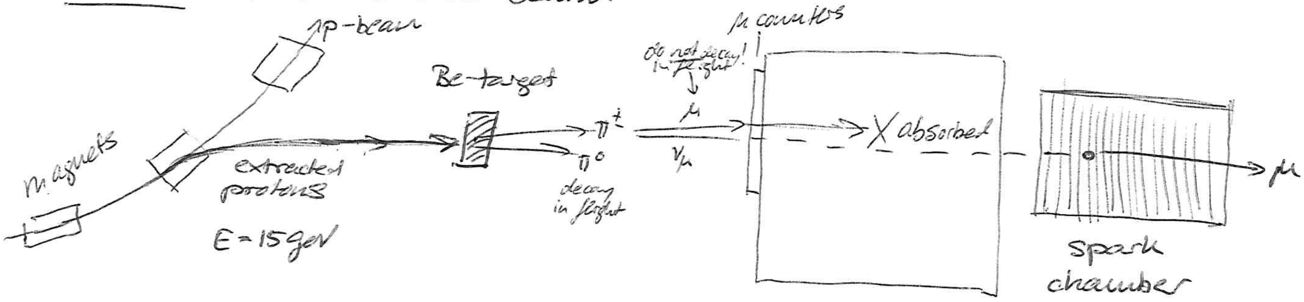
(Steinberger)

↳ L_μ conservation? L_e

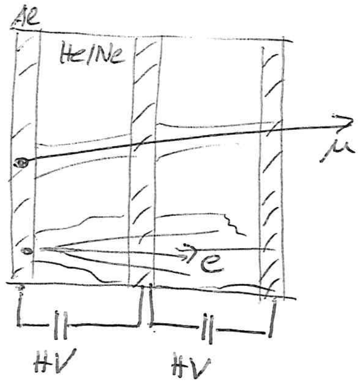
AGS Experiment

1962 Alternating gradient Synchrotron @ BNL
(Lederman, Schwartz, Steinberger)

Source: Muon neutrino beam:



Detector: Spark chamber:



Sandwich: 1m × 1m × 2.5cm Al plates
2cm interspaces filled w/ He/Ne

→ charged particles ionize gas

→ sparks between plates are created and photographed

→ μ's: low ionization, single tracks

→ e's: electromagnetic showers

→ **result:** after subtraction of BGs (cosmics etc.)
29 ν-induced muons observed $(\bar{\nu}_\mu + p \rightarrow n + \mu^+)$
no electrons $(\nu_e + n \rightarrow p + e^-)$

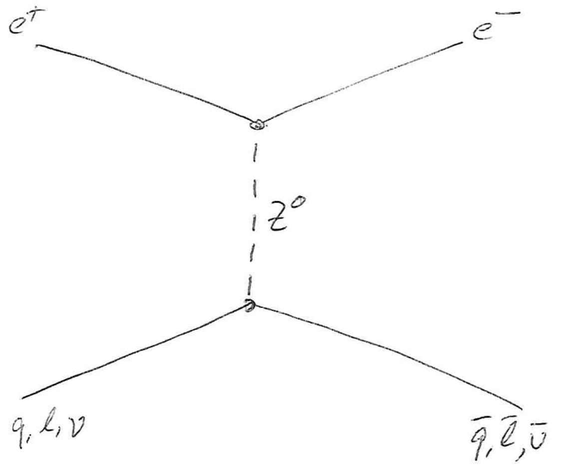
2000 DONUT experiment @ FNAL
→ First direct detection of ν_τ

Standard model: 3 generations/families/flavors

Weak doublets (charged current) $\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$

More than 3 neutrino flavors?

Z^0-decay at LEP



comparison of

Z decay width

$$\Gamma_Z = \sum_f \Gamma_f = 5\Gamma_{q\bar{q}} + 3\Gamma_{l\bar{l}} + 3\Gamma_{\nu\bar{\nu}}$$

and

Z-decay amplitude

$$A_Z = \sum_f A_f^{\text{charged}} = 5A_{q\bar{q}} + 3A_{l\bar{l}}$$

→ number of neutrinos: $N_\nu = 2.92 \pm 0.05$

two exceptions:
- heavy neutrinos: $m_\nu = m_Z/2$
- sterile neutrinos, not coupling to Z^0