1.1

Lecture 1: Introduction to neutrinos (final)

On the board before actual lecture:

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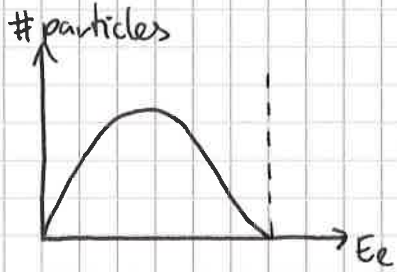
Lectures:
1. Introduction to neutrinos
2. Neutrino phenomenology } basics
3. Neutrinoless double β-decay
4. Theory of neutrino masses
5. Theory of flavour
6. Sterile neutrinos } specialised topics

Distribute literature list!

IF YOU'VE GOT A QUESTION, PLEASE INTERRUPT ME AT ANY TIME!!!

Prediction & discovery of the neutrino:

- 1930: Pauli tried to save the conservation laws in β-decay
"$(Z,A) \to (Z+1,A) + e^-$"



$\Rightarrow$ no 2-body spectrum + spin does not add up

$\Rightarrow$ saved if a third particle (electrically neutral & spin $\frac{1}{2}$) is produced $\Rightarrow$ "neutron" (renamed "neutrino" after n^0-discovery)

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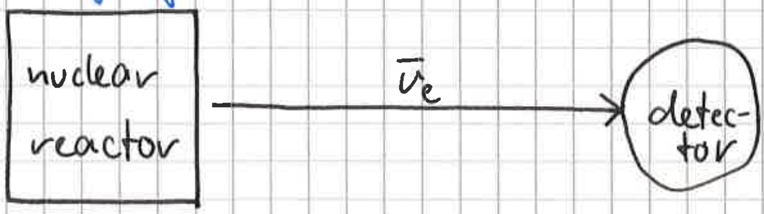
- 1942: discovery by Cowan & Reines



↳ "inverse β-decay": $\bar{\nu}_e + p^+ \longrightarrow n^0 + e^+$

detected by capture on nucleus

produces 2γ's with an e^-

⇒ since their discovery, ν's confront us with puzzles & mysteries

$\boxed{\text{Neutrinos in the SM:}}$

- known: fermion mass terms need to couple LH with RH fields
- SM:
  - quarks: $Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \sim (\underset{\uparrow\ SU(3)_c}{\underline{3}}, \underset{\uparrow\ SU(2)_L}{\underline{2}}, \underset{\uparrow\ U(1)_Y}{+\tfrac{1}{6}})$, $u_R \sim (\underline{3}, \underline{1}, +\tfrac{2}{3})$, $d_R \sim (\underline{3}, \underline{1}, -\tfrac{1}{3})$

    ⇒ Yukawa coupling: $\mathcal{L} \supset \overline{Q_L}\, \tilde{H}\, y_u\, u_R + h.c.$ ⇒ mass term with $\langle H \rangle = \binom{0}{v}$:

    $\tilde{H} = i\sigma_2 H^*$, $y_u \in \mathbb{C}^{3\times 3}$

    $\overline{Q_L}\,\underbrace{(y_u v)}_{\equiv m_u}\,u_R + h.c.$
  - leptons: $L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \sim (\underline{1}, \underline{2}, -\tfrac{1}{2})$, $e_R \sim (\underline{1}, \underline{1}, -1)$

    ↳ BUT: no ν_R

    ↳ reasons:
    - × history: ν_R not necessary (ν assumed massless)
    - × theory: —"— (not needed for anomaly cancellation)
    - × experiments: —"— (no sign of ν-mass until late '90s)
- HOWEVER: new physics?

↳ we can parametrise new physics by effective operators (non-renormalisable but using SM fields only):

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$\Rightarrow$ at $D=5$: "Weinberg operator"

$$\boxed{\mathcal{L}_5 = -\frac{y_{ij}}{\Lambda}\left(\overline{L_i^c}\,\tilde{H}^*\right)\left(\tilde{H}^\dagger L_j\right)}$$ $\Rightarrow$ Lecture 4

$\Rightarrow$ breaks lepton number

$\Rightarrow$ generates ν-mass for $\langle H\rangle \neq 0$

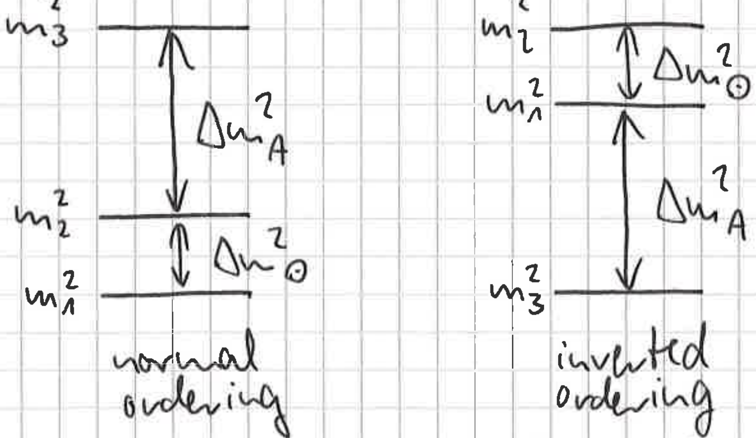
$\Rightarrow$ indicates that ν-masses lead beyond SM

Neutrino mass & mixing:

- 1998: experimental discovery of ν-oscillations $\Rightarrow$ Lecture 2
  - ↳ by now: solar / atmospheric / reactor / accelerator ν's
  - ↳ we will see: · oscillations imply $m_\nu \neq 0$ (BUT: they don't tell us the scale)
    · oscillations imply mass $\neq$ flavour
- What have we measured?
  - · Z-boson decay width $\Rightarrow$ exactly three (active) neutrinos
    - ↳ strongly supported by cosmology
  - · neutrino oscillation parameters (nu-fit.org):
    - × mass square differences: $\Delta m^2_{21} \equiv m_2^2 - m_1^2 = 7.50\cdot 10^{-5}\,\mathrm{eV}$ $\approx \Delta m^2_\odot$

$$|\Delta m^2_{31}| \equiv |m_3^2 - m_1^2| = 2.457\cdot 10^{-3}\,\mathrm{eV}^2 \;\; (\mathrm{NO}) \approx \Delta m^2_A$$
$$= 2.449\cdot 10^{-3}\,\mathrm{eV}^2 \;\; (\mathrm{IO})$$

↳ two possible mass orderings:



$\Rightarrow$ limiting cases: $m_1 \ll m_2 \ll m_3$ "normal hierarchy"

$m_3 \ll m_1 < m_2$ "inverted hierarchy"

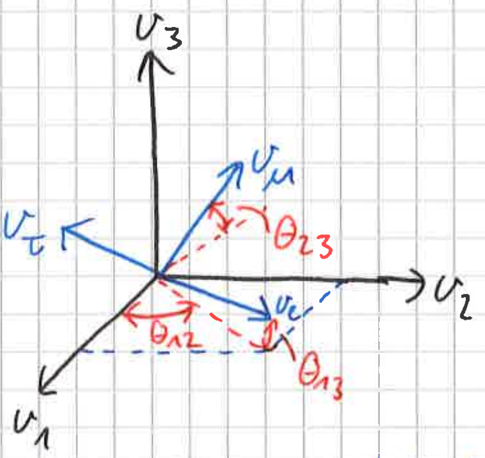
$m_1 \approx m_2 \approx m_3$ "quasi-degeneracy"

× <u>mixing angles:</u> $\theta_{12} = 33.48°$

$\theta_{13} = 8.50° \,/\, 8.51°$

$\theta_{23} = 42.3° \,/\, 49.5°$

$\Rightarrow$ <u>flavour basis $\neq$ mass basis:</u>



$\Rightarrow$ there is noting like an "electron-neutrino mass", since a ν_e is a quantum superposition of the mass eigenstates $\nu_{1,2,3}$

$\Rightarrow$ mathematically: "rotation" in flavour space

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23}-s_{12}s_{13}s_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}}_{\text{"Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix"}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

↳ δ: "Dirac CP-phase" (~ difference between matter & antimatter)

- <u>absolute mass scale:</u>
  - × single β-decay $\Rightarrow m_\nu \lesssim \mathcal{O}(1\,eV)$ } $\Rightarrow$ lecture 2
  - × cosmology $\Rightarrow m_\nu \lesssim \mathcal{O}(0.1\,eV)$ }
  - × neutrinoless double β-decay $\Rightarrow m_\nu \lesssim \mathcal{O}(0.5\,eV) \Rightarrow$ Lecture 3

Open questions in neutrino physics:

- What is the absolute neutrino mass? $\Rightarrow$ Lecture 2
- Could neutrinos be identical to their antiparticles? $\Rightarrow$ Lecture 3
- Why is the neutrino mass so small? $\Rightarrow$ Lecture 4

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- Why are the mixing angles so large? ⇒ lecture 5
- Could there be further ("sterile") neutrinos? ⇒ Lecture 6

Of course, I don't know the answers to any of these questions...

BUT: I can tell you about our current best guesses!

⇓

Start lecture 2 already if there's time!