1.1

Lecture 1: Introduction to neutrinos (final)

On the board before actual lecture:

Lecturer: Alexander Merle

Email: amerle@mpp.mpg.de

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

1.–2. basics; 3.–6. specialised topics

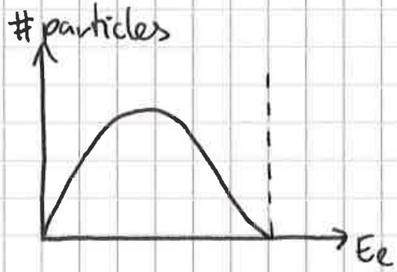
Distribute literature list!

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

"$(Z, A) \to (Z+1, A) + e^-$"



⇒ no 2-body spectrum + spin does not add up

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

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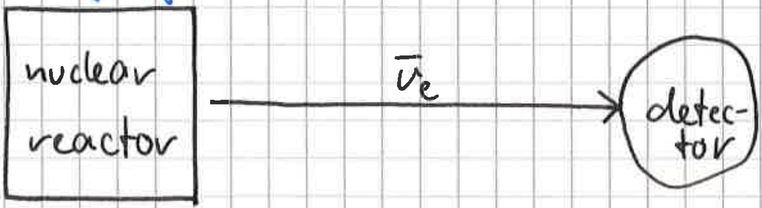
- 1942: discovery by Cowan & Reines



↳ "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

Neutrinos in the SM:

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

    $SU(3)_c$ $SU(2)_L$ $U(1)_Y$

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

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

  - leptons: $L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \sim (\underline{1}, \underline{2}, -\frac{1}{2})$, $e_R \sim (\underline{1}, \underline{1}, -1)$

    ↳ 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 untile 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"

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

$\Rightarrow$ breaks lepton number

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

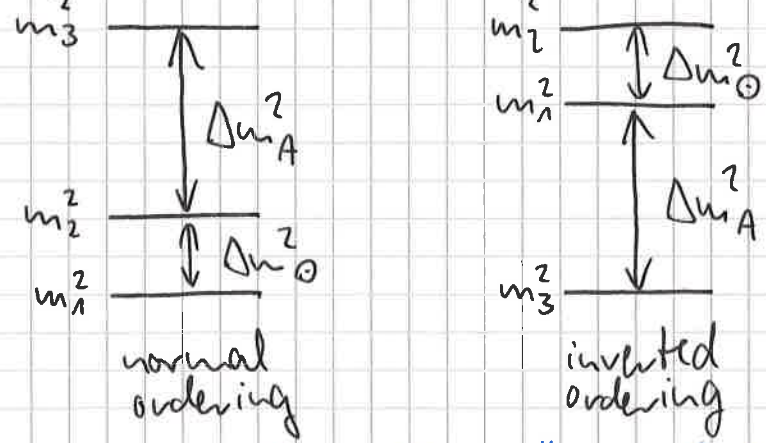
$\Rightarrow$ indicates that ν-masses lead beyond SM

Neutrino mass & mixing:

- 1998: experimental discovery of ν-oscillations $\Rightarrow$ Lecture 2
  - $\hookrightarrow$ by now: solar / atmospheric / reactor / accelerator ν's
  - $\hookrightarrow$ 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
    - $\hookrightarrow$ strongly supported by cosmology
  - neutrino oscillation parameters (nu-fit.org):
    - $\times$ mass square differences: $\Delta m_{21}^2 \equiv m_2^2 - m_1^2 = 7.50\cdot 10^{-5}\,\text{eV} \approx \Delta m_\odot^2$

$$|\Delta m_{31}^2| \equiv |m_3^2 - m_1^2| = 2.457\cdot 10^{-3}\,\text{eV}^2 \quad (\text{NO}) \approx \Delta m_A^2$$
$$= 2.449\cdot 10^{-3}\,\text{eV}^2 \quad (\text{IO})$$

$\hookrightarrow$ 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"

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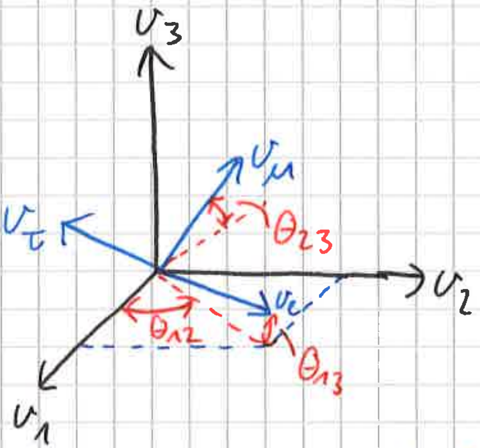
× mixing angles: $\theta_{12} = 33.48°$

$\theta_{13} = 8.50° \,/\, 8.51°$

$\theta_{23} = 42.3° \,/\, 49.5°$

⇒ flavour basis ≠ mass basis:



⇒ there is nothing like an "electron-neutrino mass", since a ν_e is a quantum superposition of the mass eigenstates $\nu_{1,2,3}$

⇒ mathematically: "rotation" in flavour space

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

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

• absolute mass scale:

× single β-decay ⇒ $m_\nu \lesssim \mathcal{O}(1\,eV)$ } ⇒ lecture 2

× cosmology ⇒ $m_\nu \lesssim \mathcal{O}(0.1\,eV)$ }

× neutrinoless double β-decay ⇒ $m_\nu \lesssim \mathcal{O}(0.5\,eV)$ ⇒ Lecture 3

$\boxed{\text{Open questions in neutrino physics:}}$

- What is the absolute neutrino mass? ⇒ Lecture 2
- Could neutrinos be identical to their antiparticles? ⇒ Lecture 3
- Why is the neutrino mass so small? ⇒ 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!