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THE NEUTRINO MASS PROBLEM

- Neutrinos $\nearrow$ Unique Probe
  $\searrow$ Intrinsic Properties

- SM choice of Chiral Fields
- Without ν_R ...
  - SM $\Rightarrow m_\nu = 0$
  - **dim. 5 WINDOW to BSM**
- With ν_R ...
  - Both m_D and m_R Masses
  - Global $U(1) \leftrightarrow m_R = 0$?
- **Facts ... and Opinions**

Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

- Particle Physics
  - $\nu N, \mu N, eN$ scattering: existence/ properties of quarks, QCD
  - Weak decays ($n \to p e^- \bar{\nu}_e, \mu^- \to e^- \nu_\mu \bar{\nu}_e$): Fermi theory, parity violation, mixing
  - Neutral current, Z-pole, atomic parity: electroweak unification, field theory, m_t; severe constraint on physics to TeV scale
  - Neutrino mass: constraint on TeV physics, grand unification, superstrings
- Astrophysics/Cosmology
  - Core of Sun
  - Supernova dynamics
  - Atmospheric neutrinos (cosmic rays)
  - AGNs, cosmic rays, violent events, GRB
  - Large scale structure (dark matter)
  - Nucleosynthesis (big bang - small A; stellar - to iron; supernova - large N)
  - Baryogenesis
  - Simultaneous probes of ν and astrophysics

② There was a time ...

1957 → Two-component ν theory

↓ Only ν_L in weak interactions

Argument in favour for $m_\nu = 0$

1958 → (V-A) theory ⇒ CHIRAL fields enter for ALL fermions

Nothing special for ν's ⟷ ν_L, e_L, N_L, q_L

No reason why $m_\nu = 0$

BUT : - e_R, q_R needed QED, QCD } ⇒ Dirac Mass $\neq 0$

- ν_R ? at will ⟷ Sterile

1967 → Standard Model "choice" : ~~ν_R~~

Dirac Mass = 0

{ No SU(2) × U(1) gauge invariant term for Majorana Mass

↓ $m_\nu = 0$

⊕ Lepton - Flavour Conservation }

BUT : - SM with total symmetry (?)

QUARKS ⟷ LEPTONS

$SU(2) \times U(1)$

Chiral Fields

Quarks

	I_3	Y	Q
u_L	$+1/2$	$1/6$	$2/3$
d_L	$-1/2$	$1/6$	$-1/3$
u_R	0	$2/3$	$2/3$
Have to... d_R	0	$-1/3$	$-1/3$

Leptons

	I_3	Y	Q
ν_L	$+1/2$	$-1/2$	0
e_L	$-1/2$	$-1/2$	-1
e_R	0	-1	-1
??? ν_R	0	0	0

- Follow the fathers of SM:

(AT PRESENT ENERGIES) $SU(2) \times U(1)$

with a particle content WITHOUT ν_R

- Is it possible (with only ν_L) to have $m_\nu \neq 0$?

A priori, YES $\longleftrightarrow$ Majorana

$$\mathcal{L}^{Maj}_{mass} = -\frac{1}{2} \bar{\nu}_L M \nu^c_L + h.c.$$

$SU(3)_{colour} \otimes U(1)_{e.m.}$ invariant $\Rightarrow$ legal

$\mathcal{L}^{Maj}$ + Pauli $\Rightarrow$ $M^T = M$

$$\downarrow$$

Diagonalization $\rightarrow$ $M = U m U^T$

$$\mathcal{L}^{Maj}_{mass} = -\frac{1}{2} \bar{\chi} m \chi$$

$$\chi \equiv U^+ \nu_L + (U^+ \nu_L)^c$$

$$\boxed{\begin{array}{c}\text{Majorana Field} \\ \chi = \chi^c = C \bar{\chi}^T\end{array}}$$

No phase-freedom to rotate away

$\Rightarrow$ Neutrinos would be "true" neutrals

- NO conserved GLOBAL LEPTON NUMBER

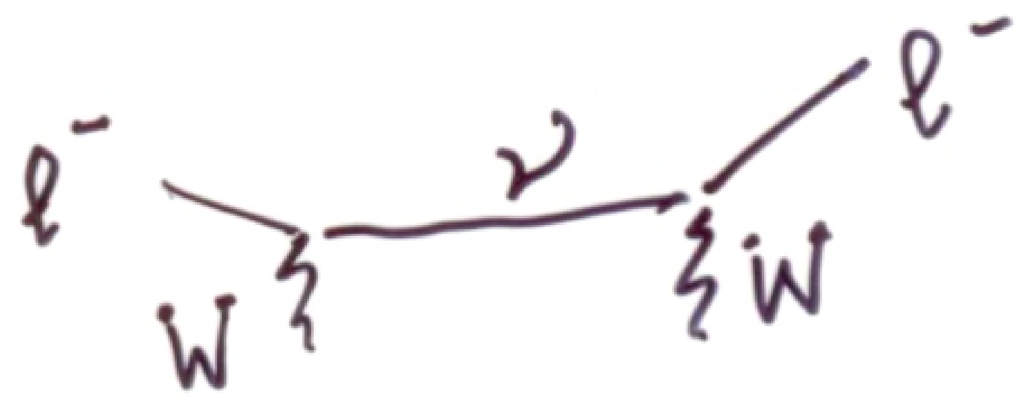
$\Rightarrow$ $\beta\beta_{0\nu}$ allowed

$$\boxed{\text{B U T ...}}$$

- Fermion Field

$$\psi(x) = \int \frac{d^3p}{(2\pi)^{3/2}} \frac{1}{\sqrt{2p^0}} \sum_\lambda \left\{ c_\lambda(p)\, u_\lambda(p)\, e^{-ipx} + d_\lambda^+(p)\, C\, [\bar{u}_\lambda(p)]^T e^{ipx} \right\}$$

- Dirac Propagator

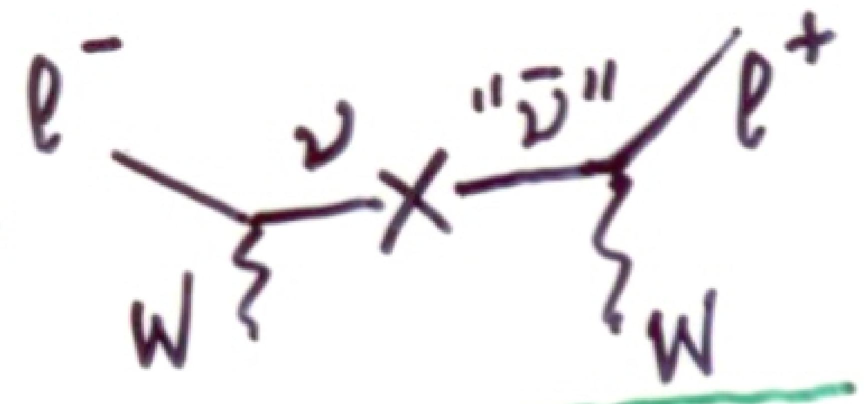


Flavour Oscillations $\Leftarrow$ $\langle 0 | T\{\psi(x)\, \bar{\psi}(0)\} | 0 \rangle$ $\boxed{\text{3 mixings, 1 phase}}$

$\exists$ for both Dirac & Majorana Neutrinos

$\equiv$ **Neutrino propagation**

- Majorana Propagator



$\langle 0 | T\{\psi(x)\, \psi(0)^T\} | 0 \rangle$ $\boxed{\text{3 mixings, 3 phases}}$

2 additional phases $\Longleftrightarrow$ $\left.\begin{array}{l} \psi \equiv \chi = C\bar{\chi}^T \\ c_\lambda(p) = d_\lambda(p) \end{array}\right\}$

$\exists$ only for Majoranas

$\equiv$ **"Neutrino-antineutrino" propagation**

- $\mathcal{L}^{Maj}_{mass}$ cannot be GENERATED by SSB of a RENORMALIZABLE (dim. 4) Yukawa interaction! Higgs triplet?

1970's → 2000's: Requirement of RENORMALIZABILITY has a different PHILOSOPHY:

- Take particle content of SM and ask WHAT IS THE LOWEST DIMENSION (NON-RENORMALIZABLE) OPERATOR WITH

SU(2) × U(1) GAUGE INVARIANCE?

UNIQUE dim. 5

$$\mathcal{L}_{eff} = -\frac{1}{2\Lambda} (\overline{\tilde{\ell}_L} \varphi) F (\tilde{\varphi}^+ \ell_L)$$

$$\tilde{\ell} = i \tau_2 \ell^c = i \tau_2 C \bar{\ell}^T$$

⇕

- The FIRST window to BEYOND SM
- $F = F^T$ matrix in flavour-space
- Coupling $\frac{1}{\Lambda}$ ⟺ $\Lambda \equiv$ New Physics Scale

⇒ 1) $\Delta L = 2$

2) F ⇒ Mixing, LFV

3) After SSB : $\mathcal{L}_{eff} \to \mathcal{L}^{Maj}_{mass}$

$$\boxed{M = \frac{v^2}{\Lambda} F}$$

"see-saw" type

Conclusion

$\mathcal{L}^{Maj}_{mass}$ for "light" neutrinos GENERATED from $\mathcal{L}_{eff}$ (at present energies).

- Origin of Λ ?
  1) Heavy mass ν_R ?
  2) Fierz-reordering

$$\mathcal{L}_{eff} = -\frac{1}{4\Lambda}\left(\bar{\tilde{l}}_L F \vec{\tau}\, l_L\right)\underbrace{\left(\tilde{\varphi}^+ \vec{\tau}\, \varphi\right)}_{\text{Higgs triplet?}}$$

- A particular example : SO(10) GUT

$\Rightarrow$ As part of SB, ν_R obtains a large Majorana mass Λ.

- The Dirac mass terms $\nu_R \leftrightarrow \nu_L$ m_D produce mixing of heavy ν_R into ν_L $\Rightarrow$ $m_\nu = \dfrac{m_D^2}{\Lambda}$

- ν_R and Yukawa interaction only

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\,\bar{l}_L M \nu_R \tilde{\varphi} + h.c.$$

$$\tilde{\varphi} = i\tau_2 \varphi^* \xrightarrow[SSB]{} \begin{Bmatrix} (v+H)/\sqrt{2} \\ 0 \end{Bmatrix}$$

⇒ Total analogy with quarks,

U CKM - matrix, ...

↓ Pontecorvo-MNS ↓

- ν's are Dirac particles
- ν_R only in Mass - terms ⇒

⇒ Masses and Mixings

- Mixing relevant for CC
- Mixing irrelevant for NC - Lagrangian

⇒ GIM - suppressed FCNC

- ν_R's do not appear elsewhere than H
- LFV, but $\mathcal{L}$ still invariant under

GLOBAL U(1) - GAUGE TRANSFORMATION

≡

TOTAL LEPTON NUMBER

WHY? BSM?

3 Is it possible (with only ν_L) to generate $m_\nu \neq 0$?

YES (a priori) ⟷ Majorana

The Pontecorvo MNS Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Leftrightarrow$$

For Flavour oscillations

U : 3 mixings, 1 phase

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\begin{array}{c}\simeq \text{Atmospheric} \\ \text{LBL - beams}\end{array}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\begin{array}{c}\simeq \text{Solar} \\ \text{Reactor (if LMA-MSW)}\end{array}}$$

? ?

Atmospheric (through Matter)?

Reactor ?

Appearance $\nu_\mu \to \nu_e$!

"Extended" SM

- $SU(2) \times U(1)$ gauge invariance
- SM + ν_R in particle content

$$\mathcal{L}(x) = -\frac{\sqrt{2}}{v}\, \bar{l}_L\, m_D\, \nu_R\, \tilde{\varphi} + h.c.$$

SU(2)×U(1) invariant

$$-\frac{1}{2}\, \bar{\nu}_R\, m_R\, (\nu_R)^c + h.c.$$

⇒ Not only L-R Dirac Mass, R-Majorana too

$$\mathcal{L}^{D-M} = -\bar{\nu}_R\, m_D\, \nu_L - \frac{1}{2}\bar{\nu}_R\, m_R (\nu_R)^c$$

$$+ h.c. \equiv -\frac{1}{2}(\bar{n}_L)^c M\, n_L + h.c.$$

$$n_L \equiv \begin{Bmatrix} \nu_L \\ (\nu_R)^c \end{Bmatrix}, \quad M = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$

⇒ Physical neutrinos ≡ MAJORANA

Unless $m_R = 0$? Why ? Global $U(1)$?

⟺ BSM

FACTS

- SM $\longleftrightarrow$ ν_L only

  $\Rightarrow$ $m_\nu = 0$

- BSM + ν_L only at present

  $\Rightarrow$ Unique window $\equiv$ dim. 5

  $\Rightarrow$ $m_\nu \neq 0$ MAJORANA

  $\Delta L = 2$ interactions at higher energies

- SM + ν_R (light)

  $\Rightarrow$ $m_\nu \neq 0$ MAJORANA

  $\Delta L = 2$ at present energies

- $m_R = 0$? $\Leftrightarrow$ U(1) - global symmetry

  $\Delta L = 0$?

  $m_\nu \neq 0$ DIRAC