Neutrinos

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Recent collaborations with

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- Esteban Roulet *(Bariloche)*
- Yael Shadmi *(Technion)*
- Alexei Smirnov *(Trieste)*

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Special thanks to

- Concha Gonzalez-Garcia
- Guy Raz

Pauli (1930)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon **a desperate remedy** to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that **my remedy could seem incredible** because one should have seen those neutrons very earlier if they really exist. **But only the one who dare can win** and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: **"Oh, It's well better not to think to this at all, like new taxes".** From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

W. Pauli

Plan of Talks

1. The Standard Model and (a Little) Beyond
2. Neutrinos (Mainly) from Heaven
3. The Numbers and What They Tell Us
4. The Flavor Puzzle(s)
5. Leptogenesis

Plan of Talk I

The Standard Model and (a Little) Beyond

1. The SM as a complete theory
2. Neutrino masses in the SM
3. The SM as an effective theory
4. Neutrino masses beyond the SM
5. The seesaw mechanism

What Are Neutrinos?

1. Spin $1/2$ - Fermions
2. $SU(3)_\mathrm{C}$ singlets - No strong interactions
3. $U(1)_\mathrm{EM}$ singlets - No EM interactions

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4a. $SU(2)$ doublets - Weak interactions (active)

4s. $SU(2)$ singlets - No weak interactions (sterile)

The Standard Model

A Particle Physics Model

1. Symmetry
2. Matter content (spin 1/2 and spin 0 fields)
3. Spontaneous symmetry breaking

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The Standard Model

1. $G_{\rm SM}$ = Local $SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$
2. (a) Spin 1/2: $3 \times$
   $\left\{Q(3,2)_{1/6} + U(3,1)_{2/3} + D(3,1)_{-1/3} + L(1,2)_{-1/2} + E(1,1)_{-1}\right\}$

   (b) Spin 0: $\phi(1,2)_{1/2}$
3. $\langle \phi^0 \rangle \neq 0 \implies G_{\rm SM} \to SU(3)_{\rm C} \times U(1)_{\rm EM}$

Fermions of the Standard Model

	Name	Color	EM-charge
$Q(3,2)_{1/6}$	Quark doublets	Yes	$+2/3, -1/3$
$U(3,1)_{2/3}$	Up-quark singlets	Yes	$+2/3$
$D(3,1)_{-1/3}$	Down-quark singlets	Yes	$-1/3$
$L(1,2)_{-1/2}$	Lepton doublets	No	$-1, 0$
$E(1,1)_{-1}$	Charged lepton singlets	No	-1

Interaction basis

Given the Standard Model

1. Symmetry
2. Particle content
3. Renormalizability (no terms of dimension $>$ mass^4)

$$\Longrightarrow \mathcal{L}_L = i\overline{L_i}\gamma_\mu \left(\partial^\mu + \frac{i}{2} g W_b^\mu \tau_b + \frac{i}{2} g' B^\mu\right) L_i - \left(Y_{ij}^\ell \overline{L_i} \phi E_j + \text{h.c.}\right)$$

Mass basis

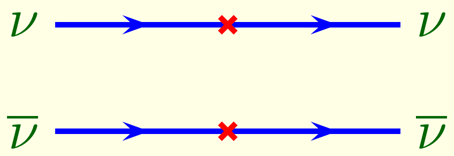
Interaction	→	Mass	
L_i		(ℓ_i^-, ν_i)	3 active ν's: ν_e, ν_μ, ν_τ
W_μ^b, B_μ		$W_\mu^\pm, Z_\mu^0, \gamma_\mu$	$Z_\mu^0 = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$
ϕ		(ϕ^+, ϕ^0)	ϕ^+ eaten by W^+

$$\Longrightarrow \; \mathcal{L}_\nu = i\overline{\nu_i}\gamma^\mu\partial_\mu\nu_i - \frac{g}{\sqrt{2}}\left(\overline{\nu_i}\gamma^\mu W_\mu^+\ell_i^- + \text{h.c.}\right) - \frac{g}{2\cos\theta_W}\overline{\nu_i}\gamma^\mu Z_\mu^0\nu_i$$

- Charged current interactions ($W^\pm$)
- Neutral current interactions (Z^0)
- No Yukawa interactions (ϕ^0)
- No mass terms

Dirac and Majorana

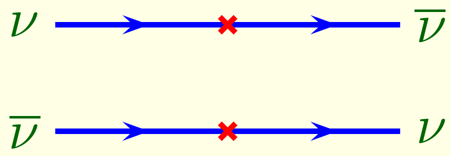
Dirac



$$\mathcal{L}_D = m_D \overline{\nu_R} \nu_L + \text{h.c.}$$

$$\Delta L = 0$$

Majorana



$$\mathcal{L}_M = \frac{m_L}{2} \overline{(\nu_L)^c} \nu_L + \text{h.c.}$$

$$\Delta L = \pm 2$$

- $\nu^c = C \bar{\nu}^T$, $C =$ charge conjugation matrix
- $\nu, \overline{\nu^c}$ annihilate ν, create $\overline{\nu}$
- $\overline{\nu}, \nu^c$ create ν, annihilate $\overline{\nu}$

$m_\nu = 0$

$$m_\nu \overline{\nu_L^c} \nu_L \ ?$$

Given the Standard Model

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$$m_\nu \overline{\nu_L^c} \nu_L \ ?$$

Given the Standard Model

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$$\Downarrow$$

Accidental $B - L$ Symmetry

$$\Downarrow$$

$$\boxed{m_\nu = 0}$$

(to all orders in perturbation theory and beyond!)

Beyond the Standard Model

Reasons Not to Believe the Standard Model

1. The fine-tuning problem
2. The strong CP problem
3. Baryogenesis
4. Gauge coupling unification
5. The flavor puzzle
6. Gravity

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Very likely, there is new physics

$$\boxed{\Lambda_{\rm EW} \ll \Lambda_{\rm NP} \leq M_{\rm Planck}}$$

SM = LEET

Very likely, the Standard Model is a low energy effective theory (LEET) valid only below a scale $\Lambda_{\rm NP} (\gg \Lambda_{\rm EW})$

$\Longrightarrow$ Renormalizability is no longer required

$$\mathcal{L} = \mathcal{L}^{\rm SM} + \frac{1}{\Lambda_{\rm NP}} O_{d=5} + \frac{1}{\Lambda_{\rm NP}^2} O_{d=6} + \cdots$$

- $B - L$ is violated by nonrenormalizable terms

Interaction basis

Given the Standard Model

1. Symmetry
2. Particle content

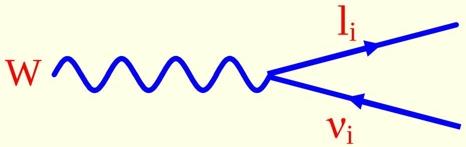
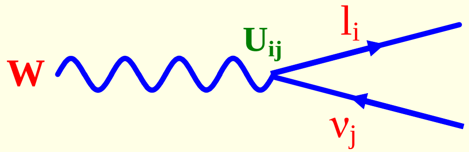
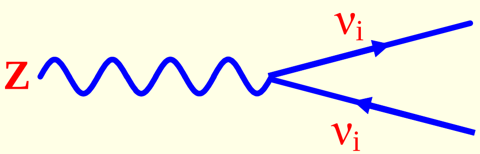
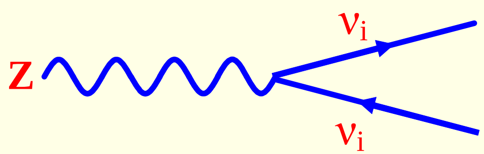
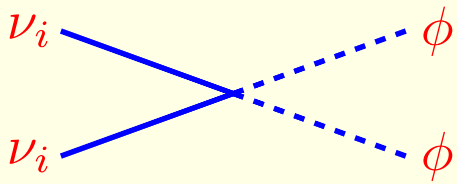
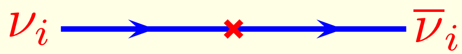
$$\mathcal{L}_L = \mathcal{L}_L^{\mathrm{SM}} + \frac{Z^{\nu}_{ij}}{\Lambda_{\mathrm{NP}}} \phi\phi L_i L_j + \mathcal{O}\left(\frac{1}{\Lambda_{\mathrm{NP}}^2}\right)$$

Mass basis

$$\begin{aligned}\mathcal{L}_\nu &= i\overline{\nu_i}\gamma^\mu\partial_\mu\nu_i - \frac{g}{2\cos\theta_W}\overline{\nu_i}\gamma^\mu Z^0_\mu\nu_i \\ &- \frac{g}{\sqrt{2}}\overline{\ell_i}\gamma^\mu U_{ij}W^-_\mu\nu_j + \text{h.c.} \\ &+ m_i\nu_i\nu_i + \text{h.c.} + \cdots\end{aligned}$$

- CC interactions involve the mixing matrix U
- Majorana mass terms: $m_i = \frac{Z_i^\nu \langle\phi\rangle^2}{\Lambda_{\rm NP}}$
- $U + m_i \implies$ 3 masses, 3 mixing angles, 3 phases

Interactions of SM=LEET

Interaction	SM	$+\frac{1}{\Lambda}LL\phi\phi$
CC		
NC		
Yukawa	None	
Masses	None	 (Majorana)

$m_\nu \neq 0$

If the SM is an effective theory, valid only below a scale $\Lambda_{\rm NP} \gg \langle\phi\rangle$

$$\Downarrow$$

- Neutrinos are massive - $\boxed{m_\nu \sim \frac{\langle\phi\rangle^2}{\Lambda_{\rm NP}}}$
- Neutrinos are light - $\frac{\langle\phi\rangle^2}{\Lambda_{\rm NP}} \ll \langle\phi\rangle$

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Examples:

- $\frac{\langle\phi\rangle^2}{\Lambda_{\rm GUT}} \sim 10^{-2}\ eV$
- $\frac{\langle\phi\rangle^2}{M_{\rm Planck}} \sim 10^{-5}\ eV$.

Cosmology:

- $m_\nu \leq \mathcal{O}(eV) \implies \Lambda_{\rm NP} \geq \mathcal{O}(10^{14}\ GeV)$

The See-Saw Mechanism (I)

SM+N

- Add to the SM $G_{\rm SM}$-singlet fermions, $N(1,1)_0$

$\Longrightarrow\ \mathcal{L}_N = Y\overline{L}\phi^\dagger N + MNN$

$$\Longrightarrow\ M_\nu = \begin{pmatrix} 0 & Y\langle\phi\rangle \\ Y\langle\phi\rangle & M \end{pmatrix}$$

- Assume $M \gg \langle\phi\rangle \ \Longrightarrow\ m_N = M, \quad m_\nu = \frac{Y^2\langle\phi\rangle^2}{M}$

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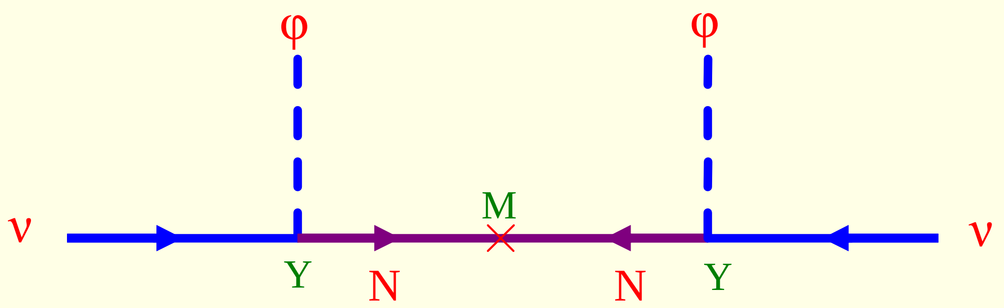
- Assume $M \gg \langle\phi\rangle \ \Longrightarrow\ m_N = M, \quad m_\nu = \frac{Y^2\langle\phi\rangle^2}{M}$

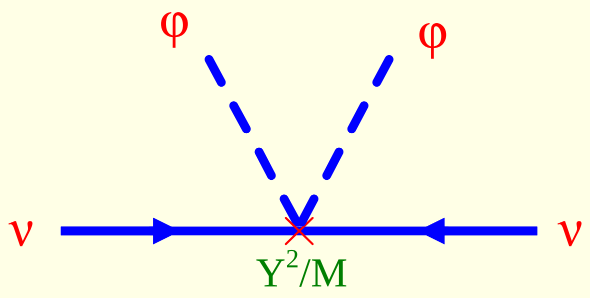
- With 3 L_i and n N_j:
  - $Y = 3\times n$ matrix, $M = n\times n$ symmetric matrix
  - $M_\nu^{\rm light} = \langle\phi\rangle^2\ Y\ M^{-1}\ Y^T$

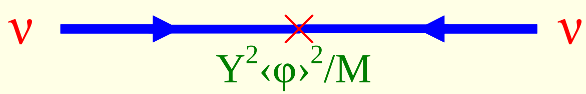
The See-Saw Mechanism

- A diagram in the SM+N:



- At energy scales $E \ll M$:





The See-Saw Mechanism (III)

$$\boxed{m_\nu = \frac{Y^2 \langle\phi\rangle^2}{M}}$$

- The heavier N, the lighter $\nu \Longrightarrow$ "The see-saw mechanism"
- A specific realization of SM=LEET, $\Lambda_{\rm NP} = M/Y^2$
- Arises in many extensions of the SM: SO(10), LRS...

Gell-Mann, Ramond, Slansky (1979)

Yanagida (1979)

Summary

Theoretical Expectations

SM $m_\nu = 0$

NP $10^{-5}\ eV \leq m_\nu \leq eV's$

$m_\nu \sim \langle\phi\rangle^2/\Lambda_{\rm NP}$

Next

Q: How to search for $m_\nu < eV$?

A: Neutrinos (mainly) from Heaven!

Counting Physical Phases (Quarks)

1. A unitary 3×3 matrix, $V^\dagger V = \mathbf{1} \Longrightarrow 3$ angles $+ 6$ phases;
2. Mass basis $\equiv M_q^{\rm diag}$ is diagonal and real;
3. Freedom in choosing phases ($P_f = {\rm diag}(e^{i\alpha_1^f}, e^{i\alpha_2^f}, e^{i\alpha_3^f})$)

$$\Downarrow$$

1. $D_L \to P_d D_L,\ D_R \to P_d D_R \quad \Longrightarrow \quad M_d^{\rm diag} \to M_d^{\rm diag}$
   $U_L \to P_u U_L,\ U_R \to P_u U_R \quad \Longrightarrow \quad M_u^{\rm diag} \to M_u^{\rm diag}$;
2. $V \to P_u^* V P_d \ \Longrightarrow$ remove 5 phases: $6 - 5 = 1$
3. An alternative proof in interaction basis:
   $M_u, M_d: \ U(3)_Q \times U(3)_U \times U(3)_D \to U(1)_B \ \Longrightarrow \ 18 - 18 + 1 = 1$

Counting Physical Phases (Leptons)

1. A unitary 3×3 matrix, $U^\dagger U = \mathbf{1} \Longrightarrow 3$ angles $+ 6$ phases;
2. Mass basis $\equiv M_\ell^{\rm diag}$ is diagonal and real;
3. Freedom in choosing phases $(P_f = {\rm diag}(e^{i\alpha_1^f}, e^{i\alpha_2^f}, e^{i\alpha_3^f}))$

$$\Downarrow$$

1. $E_L \to P_e E_L,\ E_R \to P_e E_R \quad \Longrightarrow \quad M_e^{\rm diag} \to M_e^{\rm diag}$;
   $\nu_L \to P_\nu \nu_L \quad \Longrightarrow \quad M_\nu^{\rm diag} \to P_\nu M_\nu^{\rm diag} P_\nu \quad \Longrightarrow$ not allowed;
2. $U \to P_e^* U \ \Longrightarrow$ remove 3 phases: $6 - 3 = 3$
3. An alternative proof in interaction basis:
   $M_e, M_\nu: \quad U(3)_L \times U(3)_E \to {\rm nothing} \ \Longrightarrow 15 - 12 + 0 = 3$