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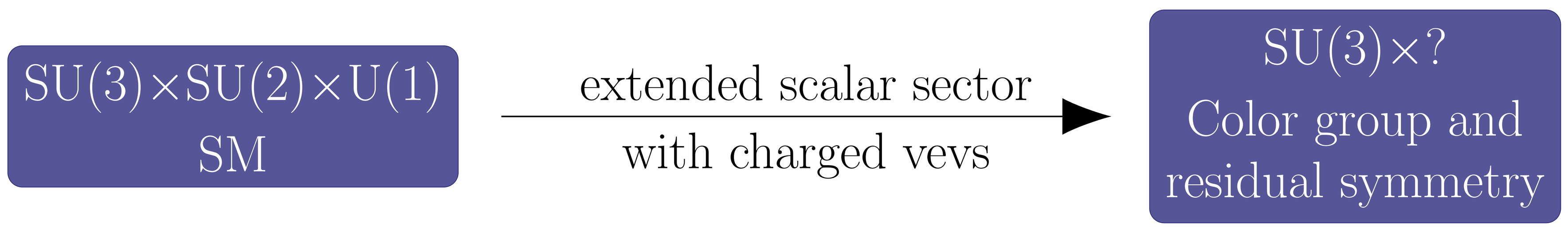
Electric Charge Breaking

in Neutrino Physics

Charge Breaking Framework

Why break electric charge?

- To provide further quantification of how well we know the standard model (SM) gauge group.
- In addition to further testing the SM, this also gives **constraints on new physics**.
- There is no *inherent* reason against charged vevs. In fact, the SM vacuum is already charged under a U(1) gauge group (i.e., hypercharge).
- While there are many experimental results constraining the breaking of $\mathrm{U}(1)_{\mathrm{Q}}$ (e.g. $M_\gamma < 10^{-18}$ eV), the theoretical side has not been studied in similar detail.



Mechanism [1]:

We add a general set of new charged scalars ϕ_i to the SM and let them obtain vevs via spontaneous symmetry breaking. In this poster, we only focus on representations such that they can interact with fermions (of which we only consider the first generation for simplicity). In order not to be excluded by measurement, this forces the assumption of very small vevs $\mathcal{O}(10^{-18}\,\mathrm{eV})$.

Direct Consequences:

- Contribution to gauge boson masses
$$M_\gamma^2 = v_i^2\,(g' y_i \cos\theta + g\,\hat{m}_i \sin\theta)^2$$
$$M_Z^2 = v_i^2\,(g' y_i \sin\theta - g\,\hat{m}_i \cos\theta)^2$$
For new vevs v_i with hypercharge y_i and $\mathrm{SU}(2)_{\mathrm{L}}$-eigenvalue $\hat{m}_i$. The weak mixing angle θ will also be slightly different from the SM.
- SM electrons and neutrinos can mix as they have the same charges in the broken phase (i.e., they are both uncharged under $\mathrm{SU}(3)_{\mathrm{C}}$).
$\Rightarrow$ They form new mass- and interaction-eigenstates, which are the electrons and neutrinos we measure.

Electron-Neutrino-Photon Interactions

- Since the **leptons can mix in the broken phase**, we need to rotate them into the new mass basis with the small angles θ_x, θ_y, and θ_z.
- Because the weak mixing angle has contributions from the new vevs, the $\mathrm{U}(1)_{\mathrm{Y}}$ and $\mathrm{SU}(2)_{\mathrm{L}}$ parts of the SM electric charge ($e_1 = g'\cos\theta$ and $e_2 = g\sin\theta$, respectively) are in general not equal any more.
- The change of basis also transforms the matrix that describes the interaction between fermions and photons:

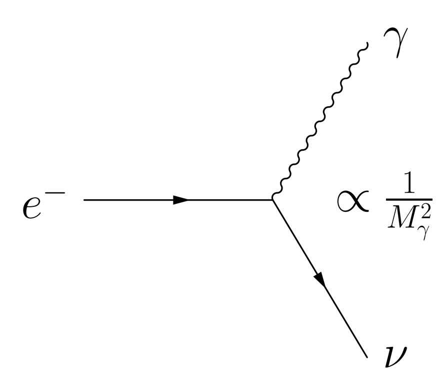
$$\begin{pmatrix}\overline{e^-_{\mathrm{L}}} & \overline{e^+_{\mathrm{L}}} & \overline{\nu_{\mathrm{L}}}\end{pmatrix} \left[\underbrace{\begin{pmatrix} e & & \\ & -e & \\ & & 0 \end{pmatrix}}_{\text{Standard Model}} \longrightarrow \underbrace{\begin{pmatrix} \frac{1}{2}(e_1+e_2) & \frac{1}{2}(3e_1+e_2)\,\theta_z & e_2\,\frac{\theta_y+\theta_x}{\sqrt{2}} \\ \frac{1}{2}(3e_1+e_2)\,\theta_z & -e_1 & \frac{3e_1-e_2}{2}\,\frac{\theta_y-\theta_x}{\sqrt{2}} \\ e_2\,\frac{\theta_y+\theta_x}{\sqrt{2}} & \frac{3e_1-e_2}{2}\,\frac{\theta_y-\theta_x}{\sqrt{2}} & \frac{1}{2}(e_1-e_2) \end{pmatrix}}_{\text{New Basis}} \right] \not{A} \begin{pmatrix} e^-_{\mathrm{L}} \\ e^+_{\mathrm{L}} \\ \nu_{\mathrm{L}} \end{pmatrix}$$

Some consequences:

- There are now interactions between electrons, neutrinos, and photons!
- There are also neutrino-neutrino-photon interactions, i.e., **the neutrino interacts weakly with electric- and magnetic-fields**.
- The same reasoning applies also to the other electroweak gauge bosons; all lepton-lepton-gauge boson interactions are possible.

Electron Decay

- When electric charge does not need to be preserved, there are lighter particles for the electron to decay to: the photon and the neutrino (and anti-neutrino, as the lepton number can be broken).
- The massive photon has an **additional third polarization**. This means that observables dependent on the photon coupling need not necessarily go smoothly to the SM limit for $M_\gamma \to 0$.
- We can compute the electron lifetime:



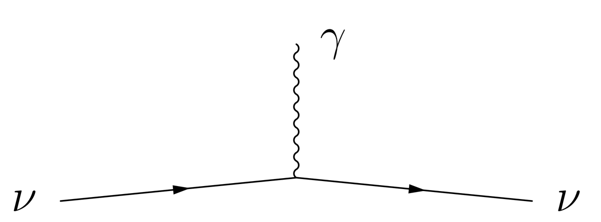
$\propto \frac{1}{M_\gamma^2}$

$$\tau \approx \frac{32\pi}{m_e e^2}\,\frac{M_\gamma^2}{M_{\mathrm{LL}}^2 + M_{\mathrm{RL}}^2} \approx 1.4\cdot 10^{-18}\,\mathrm{s}\,\frac{M_\gamma^2}{M_{\mathrm{LL}}^2 + M_{\mathrm{RL}}^2}$$

- M_{LL} is proportional to the vev of the scalar with representation $(\mathbf{1},\mathbf{1})_{-1}$ and M_{RL} to the vev of $(\mathbf{1},\mathbf{2})_{-1/2}$.
- Since we know from measurements that $M_\gamma \leq 10^{-18}\,\mathrm{eV}$ and $\tau(e^-) \geq 6.6\cdot 10^{28}\,\mathrm{yr}$, this would mean $M_{\mathrm{LL}}^2 + M_{\mathrm{RL}}^2 \leq 6.7\cdot 10^{-92}\,\mathrm{eV}^2$.
$\Rightarrow$ Having these representations with non-zero vevs at present time would require extreme fine-tuning.

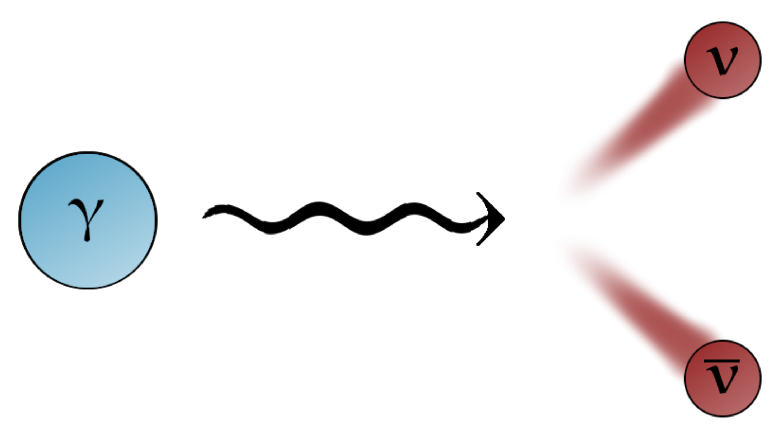
Neutrino Magnetic Moment

- Because $g'\cos\theta$ and $g\sin\theta$ are no longer exactly equal, the **tree-level coupling of the neutrino to the photon** no longer vanishes.



- This effect occurs regardless of the Majorana- or Dirac-nature of the neutrino.
- Even though electric charge is not a good quantum number anymore, we can define an **effective charge for the neutrino** $q_{\mathrm{eff}} = \frac{1}{2}(g'\cos\theta - g\sin\theta)$.
- This coupling leads to a small tree-level **contribution to the magnetic moment** of the neutrino.
$$|\mu| \sim \frac{q_{\mathrm{eff}}}{e}\mu_{\mathrm{B}}$$
- Naïvely, we expect the effective charge to be on the order of the symmetry breaking scale, i.e., $|\mu| \sim \mathcal{O}(10^{-19})\,\mu_{\mathrm{B}}$.

Photon Decay



- **The lightest neutrino** could still be lighter than the photon.
- The lifetime of the photon is then
$$\tau \approx \frac{96\pi}{M_\gamma}(g'\cos\theta - g\sin\theta)^{-2}\frac{M_\gamma^2}{M_\gamma^2 - m_\nu^2}$$
- m_ν is proportional to the vev of a SM singlet $(\mathbf{1},\mathbf{1})_0$. However, even if the neutrino receives mass with another mechanism (or remains massless), **this lifetime stays finite as long as any charged scalar has a non-zero vev**.
- Because any charge-breaking vev must be very small, we would naturally expect the phase transition to occur relatively late. The photon mass limits then imply a very high degree of time dilation. Therefore, even if the lifetime were very short, there would be little hope in measuring it.

References

[1] Florian Goertz, Manfred Lindner, and Manuel Salewski. "Exploring new frameworks for electromagnetic charge non-conservation". (in preparation).