Physics beyond the Standard Model and possible role that the neutron plays

John N Ng

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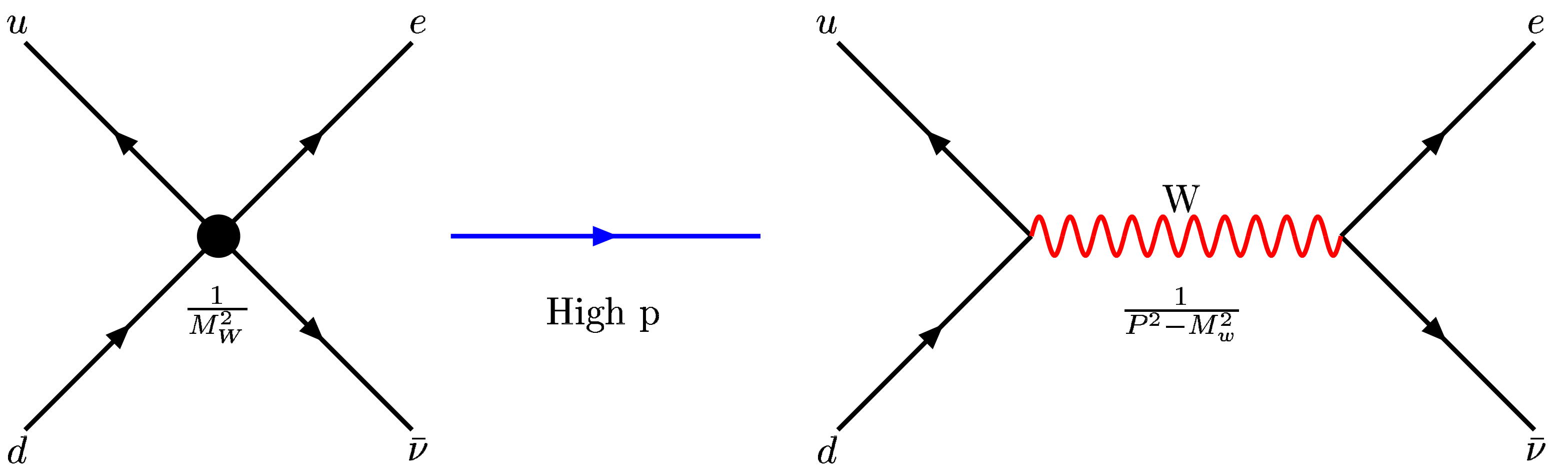
Our Missions

The aim of physics is to find new terms in the Hamiltonian of the universe.

M. Schwartz

History

- Neutron discovered by Chadwick 1932
- Pauli proposed neutrino 1930
- Fermi interaction 1934



Fermi's Paper

The paper was first submitted to *Nature* and rejected.

.... contained speculations which were far too remote from reality.

The SM

SM is a chiral gauge theory based on the semi-simple gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$

Ingredients

- Leptons ($SU(3)_c$ singlets)

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad e^c_L \quad , \; N^c_L?$$

- Quarks ($SU(3)$ triplets)

$$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad d^c_L \quad , \; u^c_L$$

Repeated 3 times for all fields except N_R?

- 8 gauge bosons for $SU(3)_c$
- 4 gauge bosons for $SU(2) \times U(1)$
- Use one complex scalar field Φ doublet under $SU(2)$ to break gauge symmetry
- Chiral only one handedness (left handed particles) is allowed by gauge invaraince.

SM Rules

- The SM is phenomenally successful.
- No one believes it is the final theory
  - (a) Too many parameters (19 + ν parameters)
  - (b) Higgs sector is unstable under quantum corrections
  - (c) Neutrino masses and fermion masses in general are not understood
  - (d) Gravity remains outside the framework
- **There must be new physics lurking behind it**
- How to find it?
  - (a) Build ever more elaborate models that solve some of the problems
  - (b) Take a Effective Theory Approach similar to Fermi's

Effective Operators

View the SM as an effective theory at the weak scale $v \sim$ 250 GeV.
The Lagrangian is then

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_5}{\Lambda_5}\mathcal{L}_5 + \frac{c_6}{\Lambda_6^2}\mathcal{L}_6 + \cdots$$

- $\mathcal{L}_{SM}$ is the SM Lagrangian and contains only dimension 4 operators
renormalizable

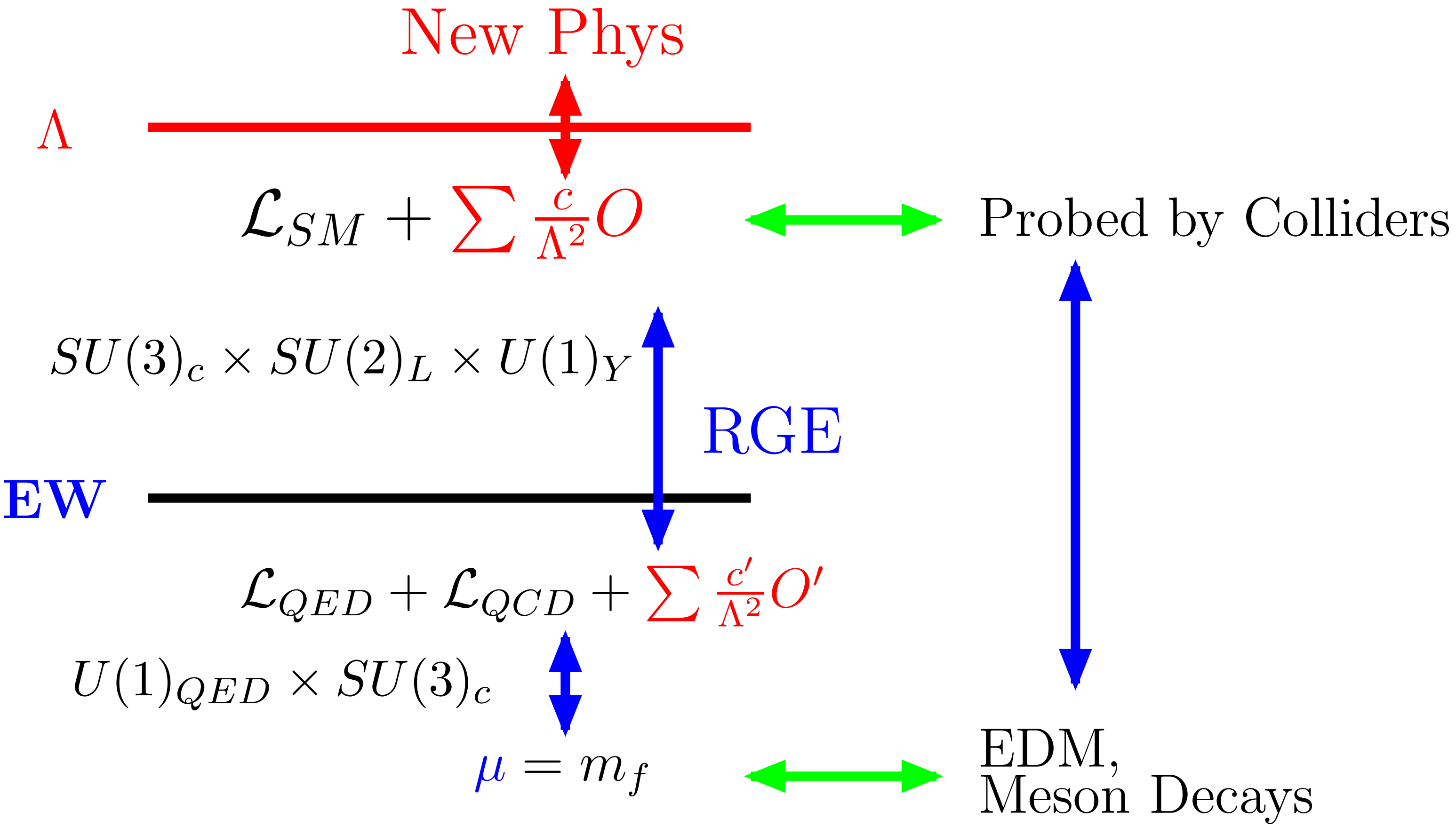
$$\begin{aligned}\mathcal{L}_{SM} &= \bar{\Psi}\gamma^{\mu}D_{\mu}\Psi - \frac{1}{4}F^{\mu\nu}\cdot F_{\mu\nu} + |D_{\mu}\Phi|^2 + y\bar{\Psi}\Psi\Phi \\ &- V(\Phi) + h.c.\end{aligned}$$

(a) $D_{\mu} = \partial_{\mu} - igT\cdot A_{\mu}$ is the covariant derivative. A_{μ} are all the gauge fields

(b) Ψ represents all the fermions of the SM 15 per family or 16 if N_R is very light or massless

(c) Φ is the Higgs field which give masses to all particles.

Effective Operators approach—Cartoon



New Phys

Λ

$\mathcal{L}_{SM} + \sum \frac{c}{\Lambda^2} O$

Probed by Colliders

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

RGE

EW

$\mathcal{L}_{QED} + \mathcal{L}_{QCD} + \sum \frac{c'}{\Lambda^2} O'$

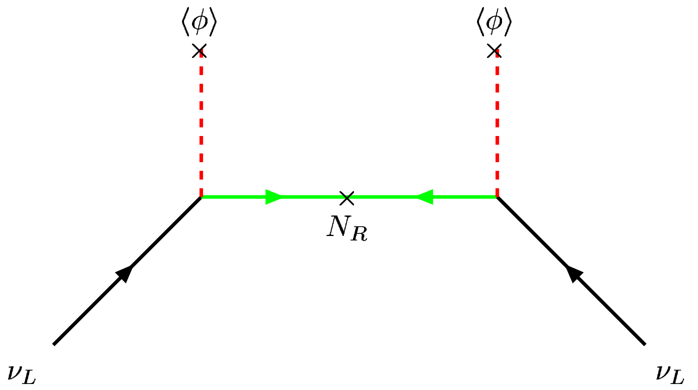
$U(1)_{QED} \times SU(3)_c$

$\mu = m_f$

EDM,
Meson Decays

Dim 5 Neutrino Mass term : Orhtodox Seesaw

- N_R is very heavy i.e.$\ggg$ TeV
- Acitve neutrino mass comes from tree level diagram



- Since N_R is heavy the propagator becomes ($M_N >> p$)

$$\frac{1}{\gamma\cdot p - M_N} \longrightarrow -\frac{1}{M_N}$$

- The effective operator is then

$$\mathcal{L}_\nu = \frac{y^2}{\Lambda_5}\nu^c\nu\Phi\Phi \xrightarrow{SSB} \frac{y^2v^2}{\Lambda_5}\nu^c\nu$$

Seesaw Neutrino Mass

- For sub-eV masses $M_N > 10^{12}$ GeV
- This is known as integrating out the heavy degrees of freedom
- We can make the identification

$$c_5 \to y^2 \quad \Lambda_5 \to M_N$$

- If this is correct we need an intermediate scale bet Fermi and Planck
- If neutrinos are Dirac particles then this term does not exist
- We have to fine tune the Yukawa's $< 10^{-12}$to get the right mass for active ν.

Why you should care about Singlet Fermions

In terms of mass matrices the cartoon is just diagoanlization of neutrino mass matrix in the basis (ν_L, N_R)

$$\begin{pmatrix} \bar{\nu_L^c} & \bar{N_R} \end{pmatrix} \begin{pmatrix} 0 & yv \\ yv & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$$

(a) $M_N \ggg yv$

- Eigenvalues are $\sim M_N$ and $m_\nu \sim \frac{y^2 v^2}{M_N}$
- The singlet or sterile neutrino **decouples** from low energy physics

(b) If $M_N = 0$ we have Dirac neutrino case. Why is this 0?

(c) If $M_N \lesssim yv$ we have sterile neutrino(s) in low energy physics

- Oscillation data and astrophysics leaves a very small window one of them $M_N \lesssim 10KeV$
- It is a low scale seesaw. Yukawa couplings still has to be fine tuned to be very small.

Constructing Effective operators

- Rule I SM Gauge Symmetry must be presereved and Lorentz Invariance.
- One one dim 5 operator O_5
- O_5 violates lepton number L
- It is well known that SM has $U(1)_{B-L}$ accidental symmetry
- Can B be violated as well? How much is allowed?
- Crucial to know the states that remain at any given scale.

Dim 6 Operators

There are many such operators.

(a) Only Gauge bosons and Higgs field; e.g.

$$G^{\mu\nu}G_{\mu\nu}\Phi\Phi$$

Modifies SM Higgs production and decay such as $\phi \to gg, \gamma\gamma$

(b) 3 gauge bosons

$$G_{\mu\rho}G^{\rho\omega}G^{\mu}_{\omega}$$

Modifies gauge boson scattering

Important at LHC

Dim 6 operators II

- Involving Two fermions gauge bosons and Higgs, important examples are the magnetic and electric dipole moment operators

$$C_D(\mu^2)\frac{1}{\Lambda^2}\bar{\Psi}_L\sigma^{\mu\nu}\Psi_R G_{\mu\nu}\phi$$

  c_D the Wilson coeff of the operator. μ is scale dependence.

- After SSB they contribute to $g-2$ and EDM d_f of the fermion involved.
- The precision which has been achieved for muon and electron limits agrees with SM loop calculations
- Any addition new physics contribution encoded in the effective operator mus obey

$$|C_D^{e,\mu}| < 10^{-10}(\Lambda/\mathrm{Te}V)$$

- We will set $c_D = 0$ at tree level

Dim 6 4-fermi operators most relevant for Low Energy Phyiscs

- The pure leptonic list of vector operators $L = (\nu e)_L \; and \; e = e_R$

$$\begin{aligned}\mathcal{L}_V^6 &= \frac{c_{LL}}{\Lambda^2}(\bar{L}_{ia}\gamma^\mu L_{ja})(\bar{L}_{kb}\gamma_\mu L_{lb}) + \frac{c_{LR}}{\Lambda^2}(\bar{L}_{ia}\gamma^\mu L_{ja})(\bar{e}_k\gamma_\mu e_l) \\ &+ \frac{c_{RR}}{\Lambda^2}(\bar{e}_i\gamma^\mu e_j)(\bar{e}_k\gamma_\mu e_l) + \frac{d_{LL}}{\Lambda^2}\left(\bar{L}_{ia}\gamma^\mu L_{jb}\right)\left(\bar{L}_{kb}\gamma_\mu L_{la}\right) \\ &+ h.c.\end{aligned}$$

- We have assumed that the coefficients are family independent.
- The scalar operators are not family independent in general

$$\mathcal{L}_s = \sum \frac{c_S^{ii,jj}}{\Lambda^2}\overline{L_i}e_{Ri}\overline{e_{Rj}}L_j + h.c.$$

- Tensor operaotrs $O_T = (\bar{L}\sigma^{\alpha\beta}e)(\bar{e}\sigma_{\alpha\beta}L)$ is identically zero.

If light Sterile Netrinos Exist

The list of additional 4-fermi operators with ν_R are

$$\begin{aligned}
Q_1 &= \left(\overline{e^i_R}\gamma^\mu \nu^j_R\right)\left(\overline{\nu^k_R}\gamma_\mu e^l_R\right)\\
Q_2 &= \left(\overline{L^i}\nu^j_R\right)\left(\overline{\nu^k_R}L^l\right)\\
Q_3 &= \left(\overline{L^i_a}e^j_R\right)\left(\overline{L^k_b}\nu^l_R\right)\epsilon^{ab}\\
Q_4 &= \left(\overline{L^i_a}\sigma^{\mu\nu} e^j_R\right)\left(\overline{L^k_b}\sigma_{\mu\nu}\nu^l_R\right)\epsilon^{ab}.
\end{aligned}$$

where a, b are $SU(2)$ indices.

These have to be included when there is evidence for $light$ sterile neutrinos.

Semileptonic 4-fermi operaotrs

- In the mass basis and with no flavor violation in vector coefficients ($i, j, k.l$ are family indices

$$-\Lambda^2 \mathcal{L}_6 = \sum_{A=1}^{7} C_{VA}^{ii,kk} O_{VA}^{ii,kk} + \sum_{A=1}^{2} C_{SA}^{ij,kl} O_{SA}^{ij,kl} + C_{T}^{ij,kl} O_{T}^{ij,kl} + h.c.$$

- The Wilson operators are

$$\begin{aligned}
O_{V1}^{ij,kl} &= (\bar{Q}^i \gamma^\mu Q^j)(\bar{L}^k \gamma_\mu L^l)\,, \\
O_{V2}^{ij,kl} &= (\bar{Q_a}^i \gamma^\mu Q_b{}^j)(\bar{L_b}^k \gamma_\mu L_a{}^k)\,, \\
O_{V3}^{ij,kl} &= (\bar{Q}^i \gamma^\mu Q^j)(\bar{e}^k \gamma_\mu e^l)\,, \\
O_{V4}^{ij,kl} &= (\bar{d}^i \gamma^\mu d^j)(\bar{L}^k \gamma_\mu L^l)\,, \\
O_{V5}^{ij,kl} &= (\bar{u}^i \gamma^\mu u^j)(\bar{L}^k \gamma_\mu L^l)\,, \\
O_{V6}^{ij,kl} &= (\bar{d}^i \gamma^\mu d^j)(\bar{e}^k \gamma_\mu e^l)\,, \\
O_{V7}^{ij,kl} &= (\bar{u}^i \gamma^\mu u^j)(\bar{e}^k \gamma_\mu e^l)\,,
\end{aligned}$$

- They affect neutral current measurements

SL operators II

- the scalar and tensor operators

$$
\begin{aligned}
O^{ij,kl}_{S1} &= (\bar{Q}^i d^j)(\bar{e}^k L^l)\,, \\
O^{ij,kl}_{S2} &= (\bar{Q_a}^i u^j)(\bar{L_b}^k e^l)\epsilon^{ab}\,, \\
O^{ij,kl}_{T} &= (\bar{Q_a}^i \sigma^{\mu\nu} u^j)(\bar{L_b}^k \sigma_{\mu\nu} e^l)\epsilon^{ab}\,,
\end{aligned}
$$

- In more familiar form for first family

$$
\begin{aligned}
O_{S1} &= (\bar{d}\hat{R}d)(\bar{e}\hat{R}e) + (\bar{u}\hat{R}d)(\bar{e}\hat{L}\nu)\,, \\
O_{S2} &= (\bar{u}\hat{R}u)(\bar{e}\hat{R}e) - (\bar{u}\hat{L}d)(\bar{e}\hat{L}\nu) \\
O_{T} &= (\bar{u}\sigma^{\mu\nu}\hat{R}u)(\bar{e}\sigma_{\mu\nu}\hat{R}e) - (\bar{d}\sigma^{\mu\nu}\hat{R}u)(\bar{\nu}\sigma_{\mu\nu}\hat{R}e)
\end{aligned}
$$

and $\hat{R} = \frac{1+\gamma^5}{2}$, $\hat{L} = \frac{1-\gamma^5}{2}$. Aslo $h.c.$.

- Thes are charged scalar and tensor currents and neutral currents in specific combinations.
- The scalar ones be probed by meson decays $\pi(K) \to l\nu$ and $K \to l\nu$.
- They are also probed in neutron beta -decay
- They also induce EDM via SM interaction terms

SL operators III

What about right-handed charged spin-1 currents?
Construction

- The quark side we need $\overline{u_R}\gamma_\mu d_R$ with $Y = -2$
- The leptonic current must then have $Y = 2$
- Not possible with the matter content of minimal SM
- If a light ν_R exists then we can have leptonic current $\overline{e_R}\gamma^\mu \nu_R$ with $Y = 2$
- The operator $\overline{u_R}\gamma_\mu d_R \overline{e_R}\gamma^\mu \nu_R$ is SM gauge invariant.
- If such a term is measured implies not only a new interaction for the right-handed fermions $also$ the existence of a light sterile neutrino.

Meson decays

At the quark level they are $d_i \to u_j l \nu_K$. The invariant amplitude is

$$\begin{aligned} i\mathcal{M} \quad &= \quad \frac{2G_F}{\sqrt{2}} f_M \Bigg[V_{ij} A(m_i) \left(P_{lk} \bar{l}\, p^\mu \gamma_\mu \hat{L}\, \nu_k \right) \\ &\quad - \frac{\sqrt{2} M^2}{4 G_F \Lambda^2 (m_i + m_j)} \left(C_{S1}^{ij,lk}(m_i) - C_{S2}^{ij,lk*}(m_i) \right) \left(\bar{l} \hat{L} \nu_k \right) \Bigg] , \end{aligned}$$

where f_m is the meson form factor. V is CKM quark mixing matrix. P is PMNS neutrinos mixing matrix

- The braching ratio for $\pi \to e\nu$ is

$$R_\pi = R_\pi^{SM} \times \left(1 + \frac{K_\pi^e - K_\pi^\mu}{G_F \Lambda^2} \right)$$

with $R_\pi^{SM} = 1.23542 \times 10^{-4}$.

$$K_\pi^l = \frac{1}{\sqrt{2} A(m_i, M_W) V_{ud}} \frac{M_\pi^2}{m_l (m_u + m_d)} \sum_k \mathfrak{Re} \left[P_{kl}^* \left(C_{S2}^{11,lk*} - C_{S1}^{11,lk} \right) \right] .$$

Limits Now

- $\pi \to e\nu$ limits the following

$$\left|\frac{K_\pi^e - K_\pi^\mu}{G_F \Lambda^2}\right| \le 0.007$$

- Implies

$$\left|\sum_k \mathfrak{Re}\left[P_{ke}^*\left(C_{S2}^{11,ke*} - C_{S1}^{11,ek}\right)\right]\right|_{\mathrm{NH}} \le 2.8 \times 10^{-5}\left(\frac{\Lambda}{\text{TeV}}\right)^2$$

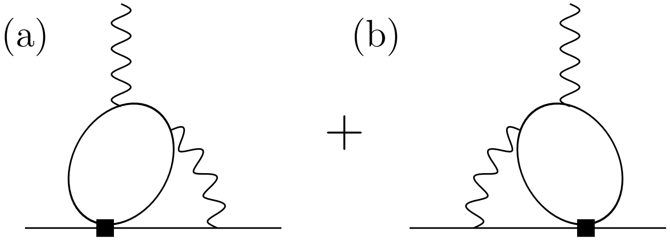
- It is possible that the terms K^e and K^μ accidentally cancels.
- Neutron beta measures one of them hence no cancellation.

Taking the SM and dim 6 Operators together

- The scalar terms and the SM will give rise to EDM
  Current experimental limit gives

$$\mathfrak{Re}\; c_s^{\mu,e} < 2.2(1\mathrm{Te}V/\Lambda)$$

- The EDM d_e, d_μ measure the $\mathfrak{Im}\; c_s$ via the 2-loop diagrams



- The limits from d_e are

$$|\mathfrak{Im}\; c_S^{e,\tau}| < 3 \times 10^{-4} \quad |\mathfrak{Im}\; c_S^{e,\mu}| < 3.3 \times 10^{-3}(1\mathrm{Te}V/\Lambda)$$

A word about Tensor Operators

They can induce an effective scalar term via radiative correction or thru Renormalization group effect

$$\frac{C_{S2}(m_P)}{C_T(m_P)} = -.036$$

Translates to

$$|\mathfrak{Re} C_T(m_p)| < 7.7 \times 10^{-4} \left(\frac{\Lambda}{\mathrm{TeV}}\right)^2$$

Some Models

- Multiple Higgs

$$\frac{c}{\Lambda^2} \to \frac{y_l y_q}{M_H^2}$$

- Extra dimensions with Kaluza-Klein Higgs

$$\frac{c}{\Lambda^2} \to \frac{y_l y_q}{M_{KK}^2}$$

- Supersymmetry with R-parity Violation

$$\to \frac{g^4}{16\pi^2 M_S^2}$$

Baryon Number violation

If neutrinos are Majorana then L is violated. Can B violation be far behind? One of the fundamental issues for neutron to probe. $n - \bar{n}$ oscillations.

- The effective operators are dim 9 (six quarks)
- There are 4 satisfying the SM gauge symmetry. Suppressing color and weak isospin indices

$$\begin{aligned}
\mathcal{N}_1 &= (u_R^T C u_R)(d_R^T C d_R)(d_R^T C d_R) \\
\mathcal{N}_2 &= (u_R^T C d_R)(u_R^T C d_R)(d_R^T C d_R) \\
\mathcal{N}_3 &= (Q_L^T C Q_L)(u_R^T C d_R)(d_R^T C d_R) \\
\mathcal{N}_4 &= (Q_L^T C Q_L)(Q_L^T C Q_L)(d_R^T C d_R)
\end{aligned}$$

- The coeff in front is $\frac{c}{\Lambda^5}$
- $\tau_{n-\bar{n}} \gtrsim 10^8$ sec $\to \Lambda > 10^5$ GeV

Observability of $n - \bar{n}$ in models

Model	Observable?
$SU(5)$	No
$SU(2)_R \times SU(2)_L \times SU(4)$	Yes
$SO(10)$	No
R Breaking MSSM	Yes
SUSY $[SU(3)]^3$	Yes
ED fermion localization	Yes

Conclusions

- Probing fundamental physics with neutron is very complementary to high energy
- It is indispensible tool in the precision measurement arena
- Search for effective scalar operators combine with π_{l2} and K_{l2} gives a complete map of these terms
- $n-\bar{n}$ oscillations gives infomation complementary to proton decay
- Possibily relates to neutrino mass generation. Especially if they are Majorana.
- EDM is a must.