



Simple Models with Baryon Number Violation but no Proton Decay

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Some Theory References

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Introduction

Standard Model (SM) has **automatic symmetry** B-L of renormalizable lagrangian. B is also an automatic symmetry classically. But its anomalous. Not important at T=0 but important at High T.

$$B = \frac{28}{79}(B - L)$$

B violated at **dimension 6**. eg. $\frac{u_R u_R d_R e_R}{\Lambda^2}$

Mean lifetime for mode $p \rightarrow e^+ \pi^0$ greater than

$$8.2 \times 10^{33} \text{ years}$$

Scale greater than about 10^{16} GeV

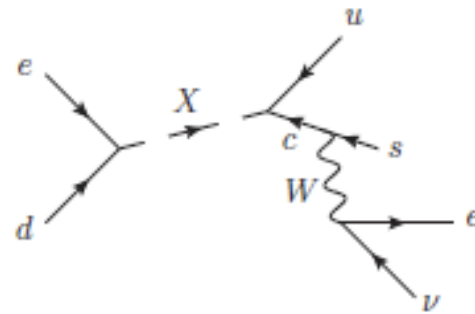
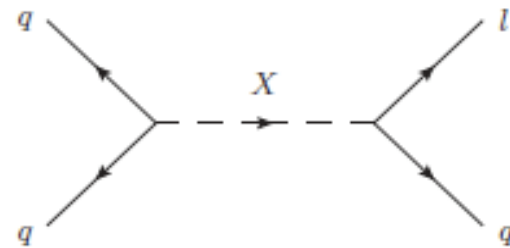
Simplest Models With Baryon number violation but no proton decay: Method

- Proton decay violates baryon number by one unit and lepton number by an odd number of units.
- Interaction violates baryon number by one unit but conserves lepton number or violates or violates baryon number by two units then no proton decay, for example.
- Can happen in supersymmetric models since there is a renormalizable operator that violates baryon number but not lepton number.
- But still could get baryon number violating process like: $n - \bar{n}$ oscillations or $p + p \rightarrow K^+ K^+$

- Simplest (least number of fields) have **two new fields** $X_{1,2}$ that couple to bilinears of quark/lepton fields:

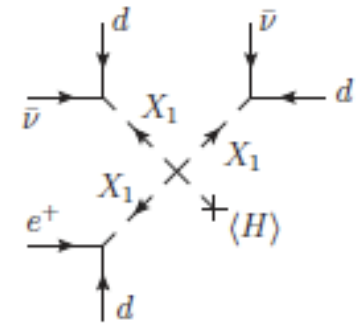
operator	$SU(3) \times SU(2) \times U(1)$ rep. of X	B	L
XQQ, Xud	$(\bar{6}, 1, -1/3), (3, 1, -1/3)_{PD}$	$-2/3$	0
XQQ	$(\bar{6}, 3, -1/3), (3, 3, -1/3)_{PD}$	$-2/3$	0
Xdd	$(3, 1, 2/3), (\bar{6}, 1, 2/3)$	$-2/3$	0
Xuu	$(\bar{6}, 1, -4/3), (3, 1, -4/3)_{PD}$	$-2/3$	0
$X\bar{Q}\bar{L}$	$(3, 1, -1/3)_{PD}, (3, 3, -1/3)_{PD}$	$1/3$	1
$X\bar{u}\bar{e}$	$(3, 1, -1/3)_{PD}$	$1/3$	1
$X\bar{d}\bar{e}$	$(3, 1, -4/3)_{PD}$	$1/3$	1
$X\bar{Q}e, XL\bar{u}$	$(3, 2, 7/6)$	$1/3$	-1
$X\bar{L}d$	$(\bar{3}, 2, -1/6)_{PD}$	$-1/3$	1
XLL	$(1, 1, 1), (1, 3, 1)$	0	-2
Xee	$(1, 1, 2)$	0	-2

- Quantum numbers (SU(3),SU(2), U(1)) that **tree level nucleon decay eliminates**: $(3,1,-1/3)$, $(3,3,-1/3)$, $(3,1,-4/3)$.
- Actually $(3,1,-4/3)$ needs **extra W boson** because of **antisymmetry**

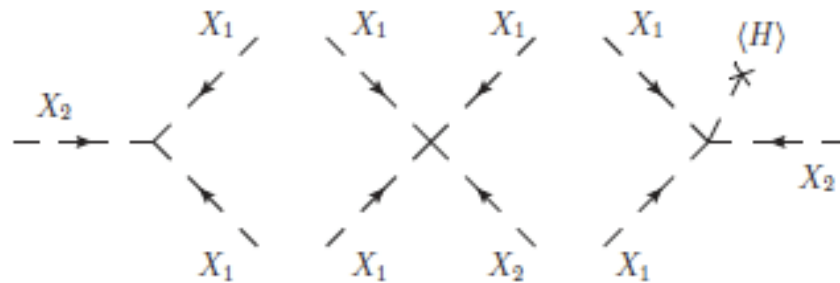


Eliminate representation $(\bar{3}, 2, -1/6)$

Gives the decay $p \rightarrow \pi^+ \pi^+ e \nu \nu$



Write most general interactions consistent with
The gauge symmetries. Violate baryon number from



The 9 Models

- Model **1**: $X_1 = (\bar{6}, 1, -1/3)$, $X_2 = (\bar{6}, 1, 2/3)$
- Model **2**: $X_1 = (\bar{6}, 3, -1/3)$, $X_2 = (\bar{6}, 1, 2/3)$
- Model **3**: $X_1 = (\bar{6}, 1, 2/3)$, $X_2 = (\bar{6}, 1, -4/3)$
- Model **4**: $X_1 = (3, 1, 2/3)$, $X_2 = (\bar{6}, 1, -4/3)$
- Model **5**: $X_1 = (\bar{6}, 1, -1/3)$, $X_2 = (1, 1, 1)$
- Etc.

$$\frac{1}{\Lambda} g^{ab} (\bar{Q}_L^{\alpha a} H) e_R^b X_\alpha .$$

Model 1

Fields: $X_1 = (\bar{6}, 1, -1/3)$, $X_2 = (\bar{6}, 1, 2/3)$

Lagrangian:

$$\begin{aligned} \mathcal{L} = & -g_1^{ab} X_1^{\alpha\beta} (Q_{L\alpha}^a Q_{L\beta}^b) - g_2^{ab} X_2^{\alpha\beta} (d_{R\alpha}^a d_{R\beta}^b) \\ & - g_1'^{ab} X_1^{\alpha\beta} (u_{R\alpha}^a d_{R\beta}^b) + \lambda X_1^{\alpha\alpha'} X_1^{\beta\beta'} X_2^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'} \end{aligned} \quad (1)$$

Coupling λ has dimensions of mass.

Baryon number violation because of λ

Coupling g_1 is antisymmetric on flavor indices,

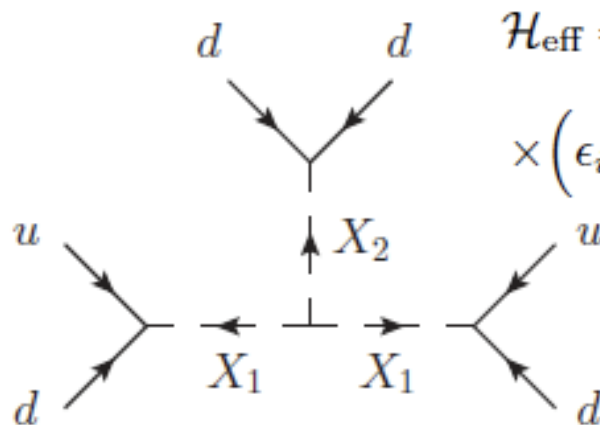
g_1' and g_2 are symmetric on flavor indices

Neutron Anti-Neutron Oscillations

Neutron anti-neutron oscillation time $\tau_{n\bar{n}} = 1/\Delta m$

$$\Delta m = \langle \bar{n} | \mathcal{H}_{eff} | n \rangle \quad P_{n \rightarrow \bar{n}} = \sin^2(t/\tau_{n\bar{n}})$$

Experiment SuperK limit, $\Delta m < 2 \times 10^{-33} \text{ GeV}$



$$\mathcal{H}_{eff} = -\frac{(g_1'^{11})^2 g_2^{11} \lambda}{4M_1^4 M_2^2} d_{Ri}^{\dot{\alpha}} d_{Ri'}^{\dot{\beta}} u_{Rj}^{\dot{\gamma}} d_{Rj'}^{\dot{\delta}} u_{Rk}^{\dot{\lambda}} d_{Rk'}^{\dot{\chi}} \epsilon_{\dot{\alpha}\dot{\beta}} \epsilon_{\dot{\gamma}\dot{\delta}} \epsilon_{\dot{\lambda}\dot{\chi}}$$

$$\times \left(\epsilon_{ijk} \epsilon_{i'j'k'} + \epsilon_{i'jk} \epsilon_{ij'k'} + \epsilon_{ij'k} \epsilon_{i'jk'} + \epsilon_{ijk'} \epsilon_{i'j'k} \right) + \text{h.c.}$$

Calculate matrix element using **vacuum insertion approximation**. One matrix element needed **between neutron three quark fields and vacuum**.

Expressed in terms of one dimensionful parameter β that has been measured using lattice QCD $\beta \simeq 0.01\text{GeV}^3$

$$|\Delta m| = 2\lambda\beta^2 \frac{|(g_1'^{11})^2 g_2^{11}|}{3M_1^4 M_2^2}$$

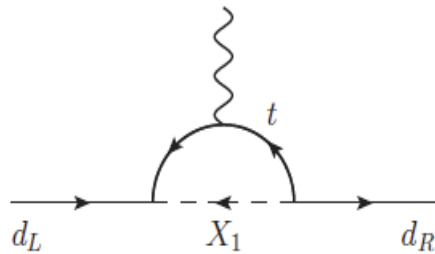
All dimensionful parameters equal to M Yukawa coupling constants equal to unity then $M > 500\text{TeV}$

Another extreme $M_1 = 5\text{TeV}$ above LHC limits.

Then with $\lambda = M_2$ find $M_2 > 5 \times 10^{13}\text{GeV}$

Flavor Physics

- Get a contribution to quark electric dipole moments not suppressed by quark mass



$$|d_d| \simeq \frac{m_t}{6\pi^2 M_1^2} \log \left(\frac{M_1^2}{m_t^2} \right) \left| \text{Im}[g_1^{31} (g_1^{\prime 31})^*] \right| ecm$$

- Experiment: $d_n^{\text{exp}} < 2.9 \times 10^{-26} ecm$

$$M_1 = 500 \text{TeV} \quad \text{then} \quad \left| \text{Im}[g_1^{31} (g_1^{\prime 31})^*] \right| \lesssim 6 \times 10^{-3}$$

- Another strong constraint from $K - \bar{K}$ mixing that arises at tree level from the exchange of X_2

$$\mathcal{H}_{\text{eff}} = \frac{g_2^{22} (g_2^{11})^*}{M_2^2} (s_{R\alpha} s_{R\beta}) (d_R^{*\alpha} s_R^{*\beta})$$

$$\rightarrow \frac{g_2^{22} (g_2^{11})^*}{2M_2^2} (\bar{d}_R^\alpha \gamma^\mu s_{R\alpha}) (\bar{d}_R^\alpha \gamma_\mu s_{R\alpha}),$$

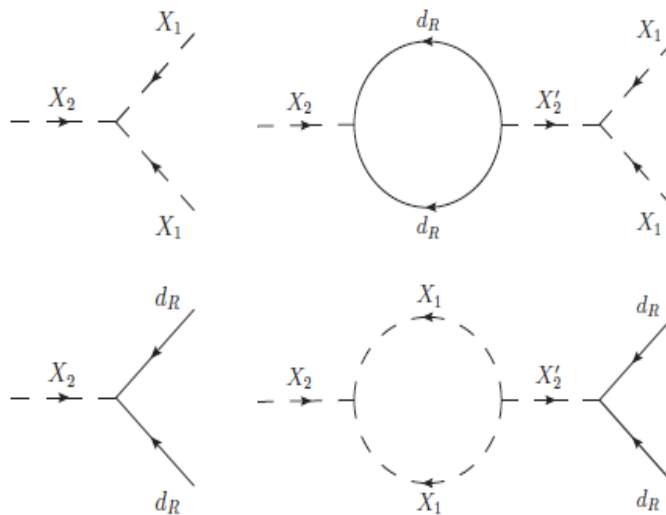
Implies that:

$$\left| \text{Re} \left[g_2^{22} (g_2^{11})^* \right] \right| < 1.8 \times 10^{-6} \left(\frac{M_2}{1 \text{ TeV}} \right)^2,$$

$$\left| \text{Im} \left[g_2^{22} (g_2^{11})^* \right] \right| < 6.8 \times 10^{-9} \left(\frac{M_2}{1 \text{ TeV}} \right)^2.$$

Generating a Baryon Asymmetry

- Use same method introduced for grand unified theories. Net baryon number per $X_2\bar{X}_2$ pair is $2(r - \bar{r})$



Decay	Br	B_f
$X_2 \rightarrow \bar{X}_1 \bar{X}_1$	r	$4/3$
$X_2 \rightarrow \bar{d}_R \bar{d}_R$	$1 - r$	$-2/3$
$\bar{X}_2 \rightarrow X_1 X_1$	\bar{r}	$-4/3$
$\bar{X}_2 \rightarrow d_R d_R$	$1 - \bar{r}$	$2/3$

LeptoQuarks

- Leptoquark models also interesting to see impact of BNV

leptoquark couplings	diquark couplings	$SU(3) \times SU(2) \times U(1)$ representation of X
$X\bar{Q}e, XL\bar{u}$	–	$(3, 2, 7/6)$
$XL\bar{d}$	–	$(3, 2, 1/6)$
$X\bar{Q}\bar{L}, X\bar{u}\bar{e}$	XQQ, Xud	$(3, 1, -1/3)_{\text{PD}}$
$X\bar{Q}\bar{L}$	XQQ	$(3, 3, -1/3)_{\text{PD}}$
$X\bar{d}\bar{e}$	Xuu	$(3, 1, -4/3)_{\text{PD}}$