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1. DIMENSION 6 OPERATORS FOR BARYON NUMBER VIOLATION IN THE STANDARD MODEL

In this note we list the lowest dimension operators which contribute to baryon number violation using only standard model fields. The constraints on these operators are: invariance under $SU(3)\times SU(2)_L\times U(1)_Y$ and Lorentz invariance. We follow [1] for a list of these operators.

1. $Q^{duql}_{prst} = (\bar{d}^{c\alpha}_p u^\beta_r)(\bar{q}^{ci\gamma}_s l^j_t)\epsilon_{\alpha\beta\gamma}\epsilon_{ij}$
2. $Q^{qque}_{prst} = (\bar{q}^{ci\alpha}_p q^{j\beta}_r)(\bar{u}^{c\gamma}_s e_t)\epsilon_{\alpha\beta\gamma}\epsilon_{ij}$
3. $Q^{qqql}_{prst} = (\bar{q}^{ci\alpha}_p q^{j\beta}_r)(\bar{q}^{ck\gamma}_s l^l_t)\epsilon_{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}$
4. $Q^{duue}_{prst} = (\bar{d}^{c\alpha}_p u^\beta_r)(\bar{u}^{c\gamma}_s e_t)\epsilon_{\alpha\beta\gamma}$

In the above we have used 4 component Dirac notation. d,u, and e refer to right handed down and up type quark fields and charged leptons, l and q are left handed SU(2) quark and lepton doublets. The superscript 'c' on a field like Ψ^c denotes the charge conjugated field operator. SU(3) indices are α, β, and γ, SU(2) indices are i, j, k, and l. Flavor indices are p, r, s, and t. To identify which combination of operators are relevant to the proton decay channel $p \to K^+\bar{\nu}$, we need just fill in the flavor structure (p, r, s, and t) from the four fermion operators above so that they contain a strange, up, and down quark, as well as a neutrino. It is easy to see that O^{qque}_{prst} and O^{duue}_{prst} do not contribute to this channel because they cannot contain a neutrino, assuming that the right handed neutrino does not exist.

Overall we find that the operators O^{duql}_{prst} and O^{qqql}_{prst} together contribute 6 terms that will allow the transition $p \to K^+\bar{\nu}$. In the following we will leave the flavor index on the lepton doublet, t, arbitrary and e^- and ν stand for any lepton doublet (electron, muon tau). From O^{duql}_{prst} we find two terms:

1. $Q^{duql}_{112t} = \epsilon_{\alpha\beta\gamma}(\bar{d}^{c\alpha}_R u^\beta_R)(\bar{c}^{c\gamma}_L e^-_L - \bar{s}^{c\gamma}_L \nu_L)$
2. $Q^{duql}_{211t} = \epsilon_{\alpha\beta\gamma}(\bar{s}^{c\alpha}_R u^\beta_R)(\bar{u}^{c\gamma}_L e^-_L - \bar{d}^{c\gamma}_L \nu_L)$

The above operators contribute because they have $sud\nu$ terms. The operator O^{qqql}_{prst} contributes 4 terms:

1. $Q^{qqql}_{112t} = \epsilon_{\alpha\beta\gamma}[(\bar{u}^{c\alpha}_L u^\beta_L)(\bar{s}^{c\gamma}_L e^-_L) - (\bar{u}^{c\alpha}_L d^\beta_L)(\bar{c}^{c\gamma}_L e^-_L) - (\bar{d}^{c\alpha}_L u^\beta_L)(\bar{s}^{c\gamma}_L \nu_L) + (\bar{d}^{c\alpha}_L d^\beta_L)(\bar{c}^{c\gamma}_L \nu_L)]$
2. $Q^{qqql}_{121t} = \epsilon_{\alpha\beta\gamma}[(\bar{u}^{c\alpha}_L c^\beta_L)(\bar{d}^{c\gamma}_L e^-_L) - (\bar{u}^{c\alpha}_L s^\beta_L)(\bar{u}^{c\gamma}_L e^-_L) - (\bar{d}^{c\alpha}_L c^\beta_L)(\bar{d}^{c\gamma}_L \nu_L) + (\bar{d}^{c\alpha}_L s^\beta_L)(\bar{u}^{c\gamma}_L \nu_L)]$
3. $Q^{qqql}_{211t} = \epsilon_{\alpha\beta\gamma}[(\bar{c}^{c\alpha}_L u^\beta_L)(\bar{d}^{c\gamma}_L e^-_L) - (\bar{c}^{c\alpha}_L d^\beta_L)(\bar{u}^{c\gamma}_L e^-_L) - (\bar{s}^{c\alpha}_L u^\beta_L)(\bar{d}^{c\gamma}_L \nu_L) + (\bar{s}^{c\alpha}_L d^\beta_L)(\bar{u}^{c\gamma}_L \nu_L)]$

From each term we can identify an $sdu\nu$ term which all together leads to the effective lagrangian

$$\begin{aligned}\mathcal{L}_{p^+\to K^+\nu} = \epsilon_{\alpha\beta\gamma}\big[&- c^{duql}_{112t}(\bar{d}^{c\alpha}_R u^\beta_R)(\bar{s}^{c\gamma}_L \nu_L) - c^{duql}_{211t}(\bar{s}^{c\alpha}_R u^\beta_R)(\bar{d}^{c\gamma}_L \nu_L) - c^{qqql}_{112t}(\bar{d}^{c\alpha}_L u^\beta_L)(\bar{s}^{c\gamma}_L \nu_L) \\ &+ c^{qqql}_{121t}(\bar{d}^{c\alpha}_L s^\beta_L)(\bar{u}^{c\gamma}_L \nu_L) + c^{qqql}_{211t}(\bar{s}^{c\alpha}_L d^\beta_L)(\bar{u}^{c\gamma}_L \nu_L) - c^{qqql}_{211t}(\bar{s}^{c\alpha}_L u^\beta_L)(\bar{d}^{c\gamma}_L \nu_L)\big]\end{aligned} \tag{1}$$

Note in the above that Q^{qqql}_{211t} contributes two terms to $p \to K^+\bar{\nu}$.

[1] R. Alonso et al., "Renormalization group evolution of dimension-six baryon number violating operators", JHEP 1404 (2014) 159 arXiv:1312.2014 [hep-ph] CERN-PH-TH-2013-305

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