Testing the unification of fundamental forces through proton decay

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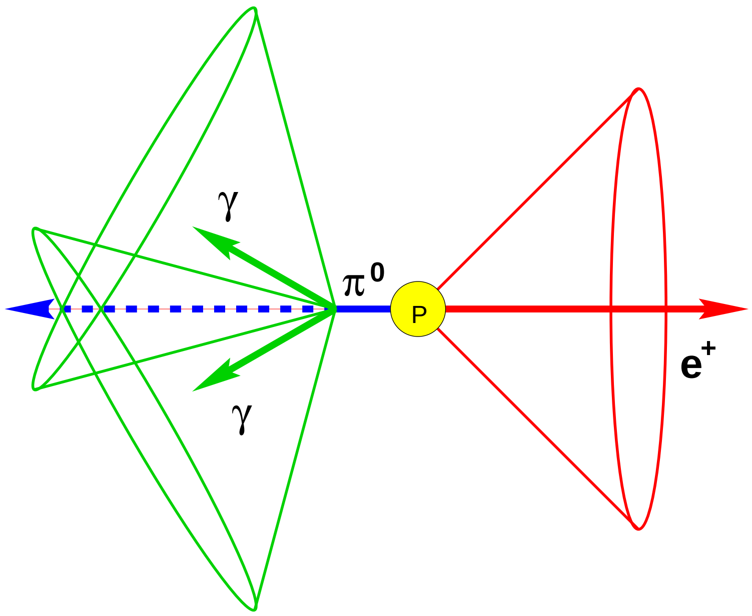

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Contents

Proton decay

In the Standard Model the Baryon number is conserved, $U(1)_B$ is a global symmetry. Therefore the lightest baryon, the proton, must be stable!

Now if the Baryon number is broken, we have a new prediction:
the decay of the proton (Pati, Salam, 1973)

$$p \to \text{meson} + \text{(anti)lepton}$$

it is a generic prediction of any grand unified theory ($SU(5)$, $SO(10)$, E_6,...)

Georgi, Glashow 1974; Georgi, 1975
Fritzsch, Minkowski, 1975

We have to look for several decay channels:

$$p \to (K^+, \pi^+, \rho^+)\bar{\nu}_i \qquad n \to (\pi^0, \rho^0, \eta, \omega, K^0)\bar{\nu}_i$$

where $i = 1, 2, 3$, and

$$p \to (K^0, \pi^0, \eta, \rho^0, \omega, \gamma)e_j^+ \qquad n \to (K^-, \pi^-, \rho^-)e_j^+$$

where $j = 1, 2$.

Channel	τ_p (10^{30} years)
$p \to invisible$	0.21
$p \to e^+\pi^0$	1600
$p \to \mu^+\pi^0$	473
$p \to \nu\pi^+$	25
$p \to e^+\eta^0$	313
$p \to \mu^+\eta^0$	126
$p \to e^+\rho^0$	75
$p \to \mu^+\rho^0$	110
$p \to \nu\rho^+$	162
$p \to e^+\omega^0$	107
$p \to \mu^+\omega^0$	117
$p \to e^+K^0$	150
$p \to e^+K^0_S$	120
$p \to e^+K^0_L$	51
$p \to \mu^+K^0$	120
$p \to \mu^+K^0_S$	150
$p \to \mu^+K^0_L$	83
$p \to \nu K^+$	670
$p \to e^+\gamma$	670
$p \to \mu^+\gamma$	478

S. Eidelman *et al.* (PDG) Phys. Lett. B **592** (2004)

Weinberg, 1979-1982; Wilczek, Zee,'79; Sakai, Yanagida,'82

Baryon number violating effective operators

$$\mathcal{L}_{eff} = c_d \frac{\mathcal{O}^d}{M^{d-4}}$$

Supersymmetric Models

$$\mathcal{O}^4_I = \Lambda_1^{cba} \int d^2\theta \; \epsilon_{ijk} \; \hat{U}^C_{ci} \; \hat{D}^C_{bj} \; \hat{D}^C_{ak}$$

$$\mathcal{O}^4_{II} = \Lambda_2^{cba} \int d^2\theta \; \epsilon_{\alpha\beta} \; \hat{Q}_{c\alpha} \; \hat{L}_{b\beta} \; \hat{D}^C_a$$

$$\mathcal{O}^5_I = \frac{C^{abcd}_{LLLL}}{M_T} \int d^2\theta \; \epsilon_{\alpha\beta} \; \epsilon_{\gamma\delta} \; \epsilon_{ijk} \; \hat{Q}_{a\alpha i} \; \hat{Q}_{b\beta j} \; \hat{Q}_{c\gamma k} \; \hat{L}_{d\delta}$$

$$\mathcal{O}^5_{II} = \frac{C^{abcd}_{RRRR}}{M_T} \int d^2\theta \; \epsilon_{ijk} \; \hat{U}^C_{ai} \; \hat{D}^C_{bj} \; \hat{U}^C_{ck} \; \hat{E}^C_d$$

$$\mathcal{O}^5_{III} = \frac{\tilde{C}^{abcd}_{RRRR}}{M_T} \int d^2\theta \; \epsilon_{ijk} \; \hat{U}^C_{ai} \; \hat{D}^C_{bj} \; \hat{D}^C_{ck} \; \hat{N}^C_d$$

where $T = (3, 1, -2/3)$ and $\overline{T} = (3^*, 1, 2/3)$

Non-Supersymmetric Contributions

Gauge $d = 6$

$$\mathcal{O}^{6}_{I} = k_1^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{u^C_{ia}} \, \gamma^\mu \, Q_{j\alpha a} \, \overline{e^C_b} \, \gamma_\mu \, Q_{k\beta b}$$

$$\mathcal{O}^{6}_{II} = k_1^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{u^C_{ia}} \, \gamma^\mu \, Q_{j\alpha a} \, \overline{d^C_{kb}} \, \gamma_\mu \, L_{\beta b}$$

$$\mathcal{O}^{6}_{III} = k_2^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{d^C_{ia}} \, \gamma^\mu \, Q_{j\beta a} \, \overline{u^C_{kb}} \, \gamma_\mu \, L_{\alpha b}$$

$$\mathcal{O}^{6}_{IV} = k_2^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{d^C_{ia}} \, \gamma^\mu \, Q_{j\beta a} \, \overline{\nu^C_b} \, \gamma_\mu \, Q_{k\alpha b}$$

where: $k_1 = g_{GUT}/\sqrt{2}M_V$, $k_2 = g_{GUT}/\sqrt{2}M_{V'}$

$V = (X, Y) = (3, 2, 5/3)$, $V' = (X^{'}, Y^{'}) = (3, 2, -1/3)$

Higgs $d = 6$

$$O_H(d_\alpha, e_\beta) = a(d_\alpha, e_\beta) \, u^T \, P_L \, C^{-1} \, d_\alpha \, u^T \, P_L \, C^{-1} e_\beta$$

$$O_H(d_\alpha, e^C_\beta) = a(d_\alpha, e^C_\beta) \, u^T \, P_L \, C^{-1} \, d_\alpha \, e^{C\dagger}_\beta \, P_L \, C^{-1} u^{C*}$$

$$O_H(d^C_\alpha, e_\beta) = a(d^C_\alpha, e_\beta) \, d^{C\dagger}_\alpha \, P_L \, C^{-1} \, u^{C*} \, u^T \, P_L \, C^{-1} e_\beta$$

$$O_H(d^C_\alpha, e^C_\beta) = a(d^C_\alpha, e^C_\beta) \, d^{C\dagger}_\alpha \, P_L \, C^{-1} \, u^{C*} \, e^{C\dagger}_\beta \, P_L \, C^{-1} u^{C*}$$

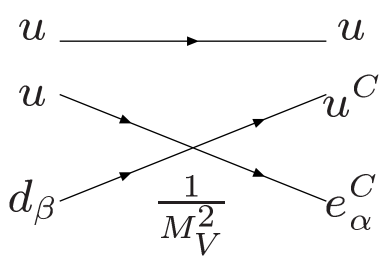
$$O_H(d_\alpha, d_\beta, \nu_i) = a(d_\alpha, d_\beta, \nu_i) \, u^T \, P_L \, C^{-1} \, d_\alpha \, d^T_\beta \, P_L \, C^{-1} \, \nu_i$$

$$O_H(d_\alpha, d^C_\beta, \nu_i) = a(d_\alpha, d^C_\beta, \nu_i) \, d^{C\dagger}_\beta \, P_L \, C^{-1} \, u^{C*} \, d^T_\alpha \, P_L \, C^{-1} \, \nu_i$$

Buras, Ellis, Gaillard, Nanopoulos '78; Hisano '00; Ellis, Nanopoulos, Walker '02; P. F. P '04

d=6 contributions: An example

Channel: $p \to \pi^0 \, e^+$ $(\tau_{exp} > 1.6 \times 10^{33}$ years)



in the physical basis we get:

$$\mathcal{O}(e_\alpha^C, d_\beta) \quad = \quad k_1^2 \, c(e_\alpha^C, d_\beta) \, \epsilon_{ijk} \, \overline{u_i^C} \, \gamma^\mu \, u_j \, \overline{e_\alpha^C} \, \gamma_\mu \, d_{k\beta}$$

Naive calculation:

$$\Gamma_6 \propto \alpha_{GUT}^2 \frac{m_p^5}{M_V^4}$$

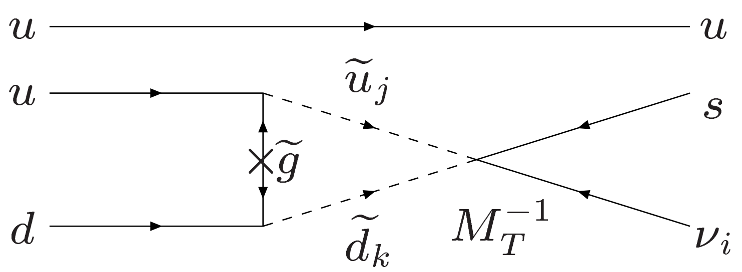
$$\alpha_{GUT} = (1/40 - 1/25) \;\; \rightarrow \;\; M_V > (2.57 - 3.23) \times 10^{15} \; GeV$$

$$M_{GUT} \sim (10^{14} - 10^{16}) \; GeV!!!$$

Dimopoulos, Raby, Wilczek '82; Arnowitt, Chamseddine, Nath '85; Hisano, Murayama, Yanagida '93; Lucas, Raby '97; Goto, Nihei '99; Nath, Syed '01; Bajc, P.F.P, Senjanovic '02.

d=5 contributions: An example

Channel: $p \to K^+ \bar{\nu}_i$ ($\tau_{exp} > 2.3 \times 10^{33}$ years)



$$A_5 \propto \frac{1}{(4\pi)^2} \frac{1}{M_T} I(m_{\widetilde{g}}, m_{\widetilde{u}_j}, m_{\widetilde{d}_k}) (\widetilde{U}^\dagger\ U)_{j1} (\widetilde{D}^\dagger\ D)_{k1} \ldots\ldots$$

where:

$$I(m, m_1, m_2) = \frac{m}{m_1^2 - m_2^2} \left(\frac{m_1^2}{m_1^2 - m^2} \ln \frac{m_1^2}{m^2} - \frac{m_2^2}{m_2^2 - m^2} \ln \frac{m_2^2}{m^2} \right)$$

In minimal SUSY $SU(5)$, assuming $m_{\widetilde{q},\widetilde{l}} \sim 1$ TeV: $M_T > 7.6 \times 10^{16}$ GeV

See: H. Murayama, A. Pierce, Phys. Rev. D65: 055009, 2002.

Note that in general we do not know $(\widetilde{U}^\dagger\ U)_{j1} (\widetilde{D}^\dagger\ D)_{k1}$!!!

The minimal supersymmetric $SU(5)$ model is not ruled out!

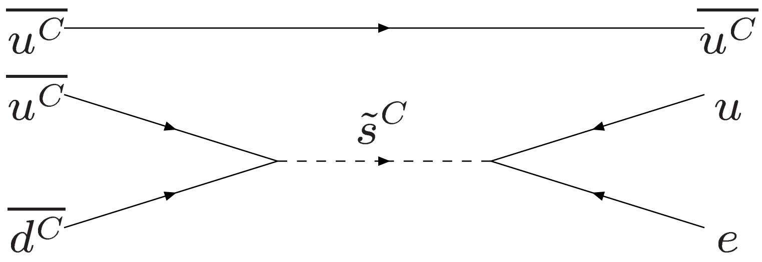
B. Bajc, P. F. P, G. Senjanović, hep-ph/0210374.

B. Bajc, P. F. P, G. Senjanović, Physical Review D **66** (2002) 075005.

See also: D. Emmanuel-Costa, S. Wiesenfeldt, Nucl. Phys. B **661** (2003) 62.

d=4 contributions: An example

Channel: $p \to \pi^0 \; e^+$ $(\tau_{exp} > 1.6 \times 10^{33}$ years)



Naive calculation:

$$\Gamma_4 \propto \frac{m_p^5}{M_{SUSY}^4}$$

$$M_{SUSY} \sim (10^3 - 10^{12}) \; GeV \;\; \to \;\; \tau_4 \sim 2.3 \times (10^{-20} - 10^{16}) \; years$$

Matter parity: $M = (-1)^{3(B-L)} = (-1)^{2S} R$

$M = -1$ for $\hat{Q}$, $\hat{L}$, $\hat{U}^C$, $\hat{D}^C$, $\hat{E}^C$; $M = 1$ for $\hat{H}$, $\hat{\overline{H}}$, and $\hat{G}_\mu$.

See for example: P. F. P, J. Phys. G **31** (2005) 1025

H. Georgi & S. L. Glashow, 1974.

S. Dimopoulos & H. Georgi, 1981.

Minimal (Non)supersymmetric $SU(5)$

$$\mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & U_3^C & -U_2^C & U_1 & D_1 \\ -U_3^C & 0 & U_1^C & U_2 & D_2 \\ U_2^C & -U_1^C & 0 & U_3 & D_3 \\ -U_1 & -U_2 & -U_3 & 0 & E^C \\ -D_1 & -D_2 & -D_3 & -E^C & 0 \end{pmatrix}_L \quad \bar{\mathbf{5}} = \begin{pmatrix} D_1^C \\ D_2^C \\ D_3^C \\ E \\ -N \end{pmatrix}_L$$

$$A(24) = G_{ij} \bigoplus (X_i, Y_i) \bigoplus (X_i^*, Y_i^*) \bigoplus (W^+, W^3, W^-) \bigoplus B^0$$

$$\mathbf{5_H} = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ H_2^+ \\ H_2^0 \end{pmatrix} \qquad \bar{\mathbf{5}}_\mathbf{H} = \begin{pmatrix} \overline{T}_1 \\ \overline{T}_2 \\ \overline{T}_3 \\ H_1^- \\ -H_1^0 \end{pmatrix}$$

$$\mathbf{\Sigma(24)} = \begin{pmatrix} \Sigma_8 & \Sigma_{(3,2)} \\ \Sigma_{(\bar{3},2)} & \Sigma_3 \end{pmatrix} + \frac{\mathbf{1}}{\mathbf{2\sqrt{15}}} \begin{pmatrix} 2 & 0 \\ 0 & -3 \end{pmatrix} \mathbf{\Sigma_{24}}$$

P. F. P, Physics Letters **B** 595 (2004) 476-483

$d=6$ nucleon decay in $SU(5)$ and $SO(10)$ theories

$SU(5)$

Matter: $10_F = (U^C, Q, E^C)$, $\bar{5}_F = (D^C, L)$ and $1_F = N^C$

Minimal Higgs sector: 5_H, $\overline{5}_H$, and 24_H.

$$\mathcal{W}_Y^{SU(5)} = 10_F \, \Gamma_U \, 10_F \, 5_H \; + \; 10_F \, \Gamma_D \, \bar{5}_F \, \bar{5}_H + \mathcal{W}_{non-renormalizable}$$

$SO(10)$: Matter unification: 16_F

Minimal Higgs sector for fermion masses: 10_H, $\overline{126}_H$.

$$\mathcal{W}_Y^{SO(10)} = 16_F \, \Gamma_{10} \, 16_F \, 10_H \; + \; 16_F \, \Gamma_{126} \, 16_F \, \overline{126}_H$$

$d=6$ operators:

$$\begin{aligned}
O(e_\alpha^C, d_\beta) &= c(e_\alpha^C, d_\beta) \, \epsilon_{ijk} \, \overline{u_i^C} \, \gamma^\mu \, u_j \, \overline{e_\alpha^C} \, \gamma_\mu \, d_{k\beta}, \\
O(e_\alpha, d_\beta^C) &= c(e_\alpha, d_\beta^C) \, \epsilon_{ijk} \, \overline{u_i^C} \, \gamma^\mu \, u_j \, \overline{d_{k\beta}^C} \, \gamma_\mu \, e_\alpha, \\
O(\nu_l, d_\alpha, d_\beta^C) &= c(\nu_l, d_\alpha, d_\beta^C) \, \epsilon_{ijk} \, \overline{u_i^C} \, \gamma^\mu \, d_{j\alpha} \, \overline{d_{k\beta}^C} \, \gamma_\mu \, \nu_l
\end{aligned}$$

with

$$c(e^C_\alpha, d_\beta) = k_1^2 \left[V_1^{11} V_2^{\alpha\beta} + (V_1 V_{UD})^{1\beta} (V_2 V_{UD}^\dagger)^{\alpha 1} \right]$$

$$c(e_\alpha, d^C_\beta) = k_1^2 \; V_1^{11} V_3^{\beta\alpha} + \; k_2^2 \; (V_4 V_{UD}^\dagger)^{\beta 1} (V_1 V_{UD} V_4^\dagger V_3)^{1\alpha}$$

$$c(\nu_l, d_\alpha, d^C_\beta) = k_1^2 \; (V_1 V_{UD})^{1\alpha} (V_3 V_{EN})^{\beta l} + k_2^2 \; V_4^{\beta\alpha} (V_1 V_{UD} V_4^\dagger V_3 V_{EN})^{1l}$$

$\alpha = 1$ or $\beta = 1$.

where $V_1 = U_C^\dagger U$, $V_2 = E_C^\dagger D$, $V_3 = D_C^\dagger E$, $V_4 = D_C^\dagger D$,

$V_{UD} = U^\dagger D$, $V_{EN} = E^\dagger N$, $V_{UD} = U^\dagger D = K_1 V_{CKM} K_2$,
$V_{EN} = K_3 V_l^D K_4$ or $V_{EN} = K_3 V_l^M$.

$$U_C^T \; Y_U \; U = Y_U^{diag}, \;\; D_C^T \; Y_D \; D = Y_D^{diag}, \;\; E_C^T \; Y_E \; E = Y_E^{diag};$$

$k_1 = g_{GUT}/\sqrt{2} M_V$ & $k_2 = g_{GUT}/\sqrt{2} M_{V'}$

$(X, Y) = (\mathbf{3}, \mathbf{2}, 5/3)$, $Q(X) = 4/3$ & $Q(Y) = 1/3$.

$(X', Y') = (\mathbf{3}, \mathbf{2}, -1/3)$, $Q(Y') = -2/3$ &

$Q(X^{'}) = Q(Y)$. $\alpha, \beta = 1, 2$, $l = 1, 2, 3$.

P. F. P, Physics Letters **B** 595(2004) 476-483

$p \to K^+\bar{\nu}$ and $p \to \pi^+\bar{\nu}$ channels and the test of GUT's

$$k_1 = \frac{g_{GUT}}{\sqrt{2}M_V} = \left[\frac{Q_1\ \Gamma^{exp}(p \to K^+\bar{\nu})}{|A_1|^2 \left|V_{CKM}^{11}\right|^2 + |A_2|^2 \left|V_{CKM}^{12}\right|^2}\right]^{1/4}$$

with:

$$Q_1 = \frac{8\pi m_p^3 f_\pi^2}{(m_p^2 - m_K^2)^2 A_L^2 \left|\alpha\right|^2}, \quad A_1 = \frac{2m_p}{3m_B} D, \quad A_2 = 1 + \frac{m_p}{3m_B}(D + 3F)$$

$$k_2 = \frac{g_{GUT}}{\sqrt{2}M_{V'}} = k_1 \left|V_{CKM}^{11}\right| \{-1 + \sqrt{Q_2}\}^{1/2}$$

$$Q_2 = 1 + \frac{8\pi f_\pi^2\ \Gamma^{exp}(p \to \pi^+\bar{\nu})}{k_1^4 \left|V_{CKM}^{11}\right|^4 m_p A_L^2 \left|\alpha\right|^2 (1 + D + F)^2} - \left|V_{CKM}^{11}\right|^{-2}$$

$$\frac{\tau(p \to K^+\bar{\nu})}{\tau(p \to \pi^+\bar{\nu})} > 30$$

Neutron decays:

$$\frac{\tau(n \to K^0\bar{\nu})}{\tau(p \to K^+\bar{\nu})} = 0.37, \quad \frac{\tau(n \to \pi^0\bar{\nu})}{\tau(p \to \pi^+\bar{\nu})} = 1.99, \quad \frac{\tau(n \to \eta^0\bar{\nu})}{\tau(p \to \pi^+\bar{\nu})} = 54.50$$

I. Dorsner, P. F. P, Physics Letters B **625** (2005) 88-95

Upper bound on the proton lifetime in GUTs

In the case of Majorana neutrinos

$$\tau_p^M \leq 6.0 \times 10^{39} \frac{(M_X/10^{16}\,\mathrm{GeV})^4}{\alpha_{GUT}^2} (0.003\,\mathrm{GeV}^3/\alpha)^2 \,\mathrm{years}$$

Using ($\tau_p \geq 50 \times 10^{32}$ years) and $\alpha = 0.003\,\mathrm{GeV}^3$, the bound on M_X read as:

$$M_X \;>\; 3.04 \times 10^{14} \sqrt{\alpha_{GUT}}\,\mathrm{GeV}$$

if $\alpha_{GUT} = 1/39 - 1/25$:

$$M_X \;>\; (4.9 - 6.1) \times 10^{13}\,\mathrm{GeV}$$

In the case of Dirac neutrinos

$$\tau_p^D \leq 1.4 \times 10^{37} \frac{(M_X/10^{16}\,\mathrm{GeV})^4}{\alpha_{GUT}^2} (0.003\,\mathrm{GeV}^3/\alpha)^2 \,\mathrm{years}$$

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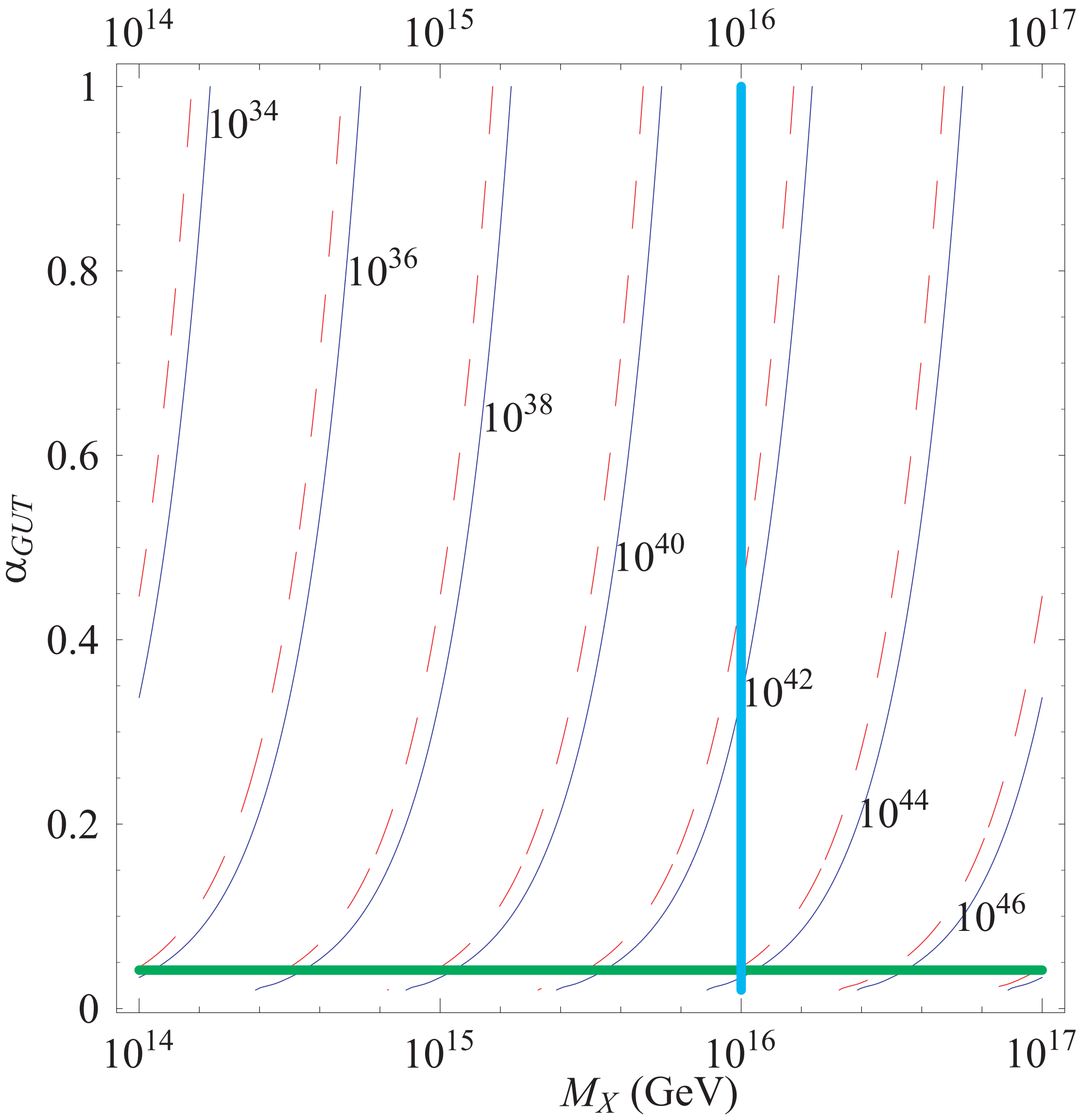

Figure 1: Isoplot for the upper bounds on the total proton (solid lines) and neutron (dashed lines) lifetimes in years in the Majorana neutrino case in the M_X–α_{GUT} plane. The value of the unifying coupling constant is varied from 0.02 to 1.

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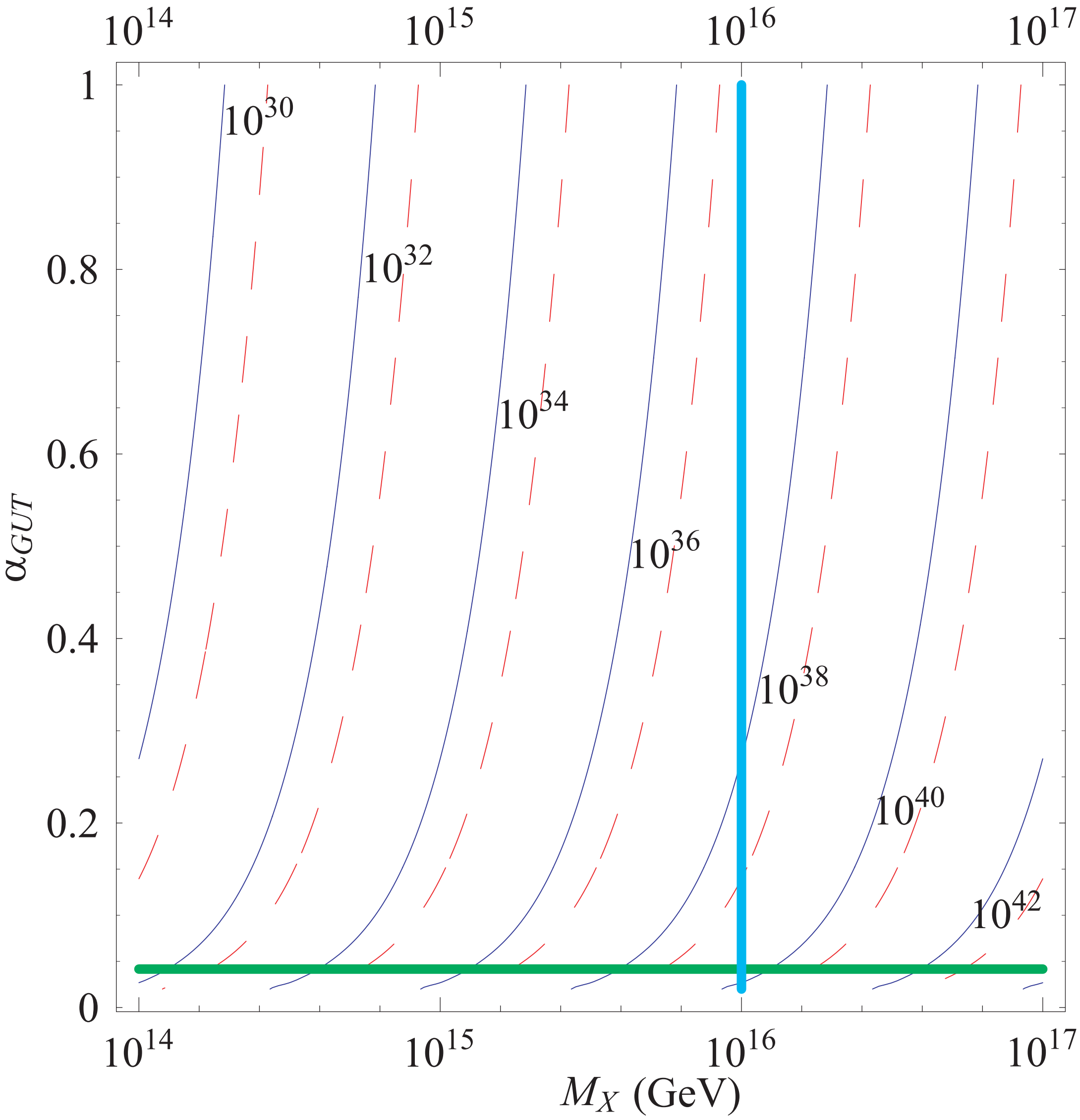

Figure 2: Isoplot for the upper bounds on the total proton (solid lines) and neutron (dashed lines) lifetimes in years in the Dirac neutrino case in the M_X–α_{GUT} plane. The value of the unifying coupling constant is varied from 0.02 to 1.

Summary

- The $d = 5$ contributions are quite model dependent.

  The minimal supersymmetric grand unified theories (e.x. SUSY SU(5)) are not ruled out

- The channels $p \to K^+ \bar{\nu}$ and $p \to \pi^+ \bar{\nu}$ can help us to test most of the realistic grand unified theories.

- There is a conservative model independent upper bound on the total proton decay lifetime:

$$\tau_p^M \leq 6.0 \times 10^{39} \frac{(M_X / 10^{16}\,\mathrm{GeV})^4}{\alpha_{GUT}^2} \left(0.003\,\mathrm{GeV}^3/\alpha\right)^2 \mathrm{years}$$