NUCLEON DECAY IN THE LIGHT OF NEUTRINO MASSES

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OSAKA, JAPAN

- SUPERKAMIOKANDE ATMOSPHERIC ν-DATA STRONG EVIDENCE FOR ν-MASSES

$$\Delta m^2_{atm} = (10^{-3} - 10^{-2})\ eV^2$$

$$\sin^2 2\theta_{atm} = (0.8 - 1.0)$$

- SOLAR ν EXPERIMENTS $\Rightarrow$

$$\Delta m^2_{Solar} = (4-15) \times 10^{-6}\ eV^2$$

$$\sin^2 2\theta_{Solar} = \begin{cases} (4-14) \times 10^{-3} \\ (0.4-0.9) \end{cases}$$

SMALL ANGLE MSW

LARGE ANGLE MSW

- VACUUM OSCILLATION SOLUTION $\Rightarrow$

$$\Delta m^2_{Solar} \simeq 10^{-10}\ eV^2$$

$$\sin^2 2\theta_{Solar} = (0.8 - 1.0)$$

- IN ADDITION, LSND $\bar{\nu}_\mu - \bar{\nu}_e$ OSCILLATION DATA $\Rightarrow$

$$\Delta m^2_{LSND} \approx 1\ eV^2$$

$$\sin^2 2\theta_{LSND} \approx 10^{-2}$$

- UNIFIED THEORIES BASED ON THE GAUGE GROUP SO(10) ARE ATTRACTIVE EXTENSIONS OF STANDARD MODEL

SO(10)

- UNIFIES ALL MEMBERS OF A FAMILY
- PREDICTS SMALL ν-MASSES VIA SEESAW MECHANISM
- PREDICTS GAUGE COUPLING UNIFICATION CORRECTLY - WITH SUSY

- NEUTRINO MASSES SIGNIFICANTLY MODIFY OUR EXPECTATIONS FOR NUCLEON DECAY

Structure of Matter Multiplets

$$\boxed{Q} = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$\boxed{u^c} = (\, u_1^c \quad u_2^c \quad u_3^c \,) \sim (\overline{3}, 1, \frac{-2}{3})$$

$$\boxed{d^c} = (\, d_1^c \quad d_2^c \quad d_3^c \,) \sim (\overline{3}, 1, \frac{1}{3})$$

$$\boxed{L} = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

$$\boxed{e^c} \quad \sim (1, 1, +1)$$

$$\boxed{\nu^c} \quad \sim (1, 1, 0)$$

$u_1 : \quad |\uparrow\downarrow\uparrow\uparrow\downarrow>$

$u_2 : \quad |\uparrow\downarrow\uparrow\downarrow\uparrow>$

$u_3 : \quad |\uparrow\downarrow\downarrow\uparrow\uparrow>$

$d_1 : \quad |\downarrow\uparrow\uparrow\uparrow\downarrow>$

$d_2 : \quad |\downarrow\uparrow\uparrow\downarrow\uparrow>$

$d_3 : \quad |\downarrow\uparrow\downarrow\uparrow\uparrow>$

$u_1^c : \quad |\downarrow\downarrow\uparrow\downarrow\downarrow>$

$u_2^c : \quad |\downarrow\downarrow\downarrow\uparrow\downarrow>$

$u_3^c : \quad |\downarrow\downarrow\downarrow\downarrow\uparrow>$

$d_1^c : \quad |\uparrow\uparrow\uparrow\downarrow\downarrow>$

$d_2^c : \quad |\uparrow\uparrow\downarrow\uparrow\downarrow>$

$d_3^c : \quad |\uparrow\uparrow\downarrow\downarrow\uparrow>$

$\nu : \quad |\uparrow\downarrow\downarrow\downarrow\downarrow>$

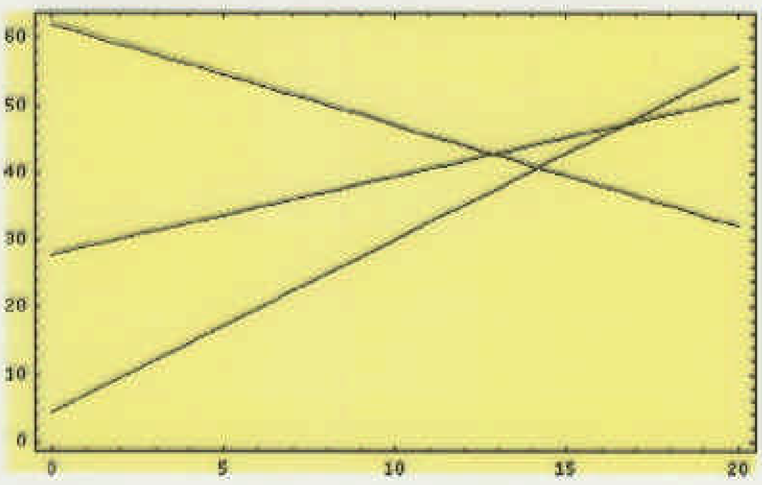
$e : \quad |\downarrow\uparrow\downarrow\downarrow\downarrow>$

$e^c : \quad |\downarrow\downarrow\uparrow\uparrow\uparrow>$

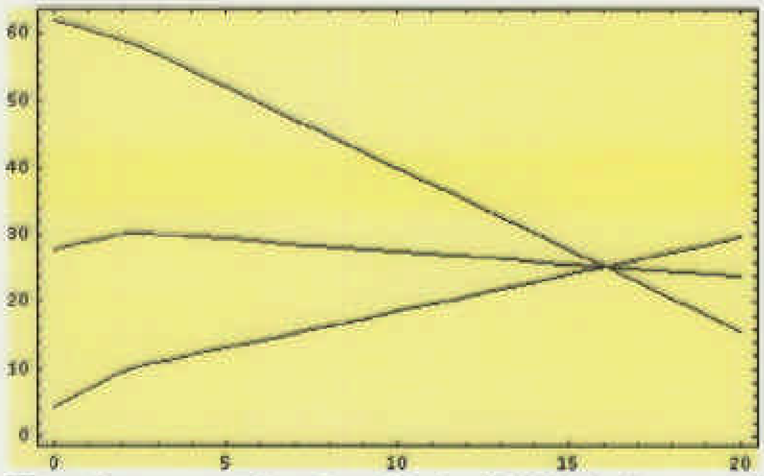
$\nu^c : \quad |\uparrow\uparrow\uparrow\uparrow\uparrow>$

Experimental evidence for supersymmetry: the running of coupling constants for the Standard Model and its minimal supersymmetric extension

The Standard Model



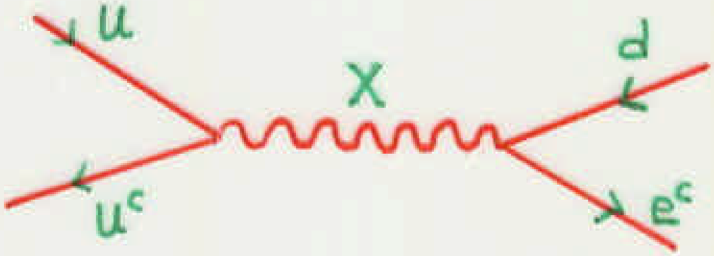
MSSM



These figures are taken from U. Amaldi, W. de Boer, and H. Furstenau, *Phys. Lett.* **B260** (1991) 447-455. For the MSSM, the slope of the running of the coupling constant has a discontinuity at M_{SUSY}. Here, M_{SUSY} was adjusted such that all three coupling constants will actually meet at some M_{GUT}. Because we had one free paramtameter to adjust, the fact that coupling constant converged at a single point alone is not especially remarkable. What makes MSSM special is the fact that it predicts the proton decay life time of the order $10^{33.2+/-1.2}$ yr which does not contradict the experimental limits of $t > 10^{32}$ yr.

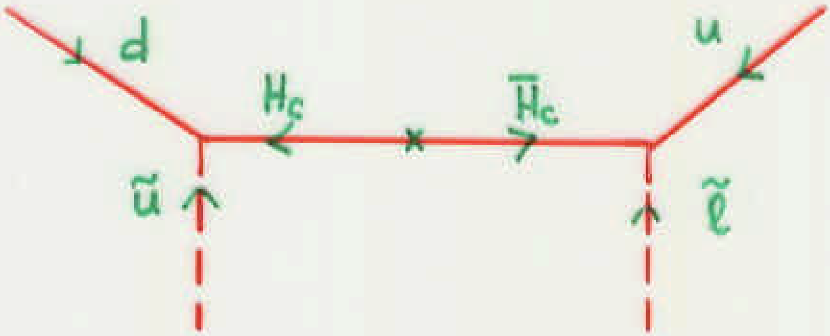
NUCLEON DECAY IN SUSY GUTs

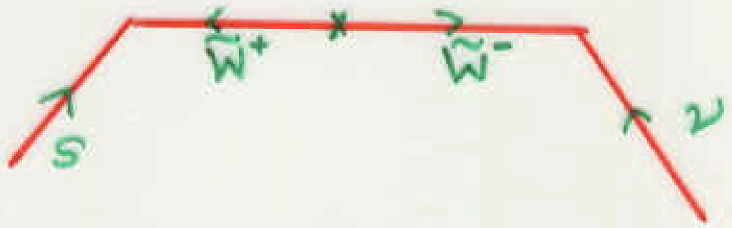
1.



$$\tau_p^{-1} \approx \left[\frac{g^2}{M_X^2}\right]^2 m_p^5 = \left[10^{36\pm1}\ yr\right]^{-1}$$

2. HIGGSINO EXCHANGE





$$\tau_p^{-1} \approx \left[\frac{f^2}{M_{H_c} M_{SUSY}}\right]^2 \left(\frac{\alpha}{4\pi}\right)^2 m_p^5$$

$$\approx \left[(10^{28} - 10^{34})\ \mathrm{yr}\right]^{-1}$$

IN MINIMAL SUSY SU(5),

$$\Gamma^{-1}(p \to \bar{\nu} K^{+}) \simeq$$

$$(5\times 10^{31}\,yr)\left(\frac{0.006}{\beta_H}\right)^2\left(\frac{1/6}{m_{\tilde{W}}/m_{sq}}\right)^2\left(\frac{m_{sq}}{1\,TeV}\right)^2\left(\frac{3}{\tan\beta}\right)^2\left(\frac{m_{H_C}}{2\times 10^{16}\,GeV}\right)^2$$

(Hisano, Murayama, Yanagida
Arnowitt, Nath)

CONCRETE SO(10) MODEL

BABU, PATI, WILCZEK, NUCL. PHYS. B566, 33 (2000)

ASSUMPTIONS

- MINIMAL HIGGS CONTENT
  $\{45, 16+\overline{16}, 10+10'\}$
- CONSTRAINED SYSTEM OF QUARK AND LEPTON MASSES AND MIXINGS — INCLUDING LARGE ν_μ-ν_τ OSCILLATION
- NATURAL DOUBLET-TRIPLET SPLITTING

PREDICTIVE FERMION SECTOR

$$U = \begin{bmatrix} 0 & \epsilon' & 0 \\ -\epsilon' & 0 & \epsilon+\sigma \\ 0 & -\epsilon+\sigma & 1 \end{bmatrix} m_U \; ; \quad D = \begin{bmatrix} 0 & \epsilon'+\eta' & 0 \\ -\epsilon'+\eta' & 0 & \epsilon+\eta \\ 0 & -\epsilon+\eta & 1 \end{bmatrix} m_D$$

$$N = \begin{bmatrix} 0 & -3\epsilon' & 0 \\ 3\epsilon' & 0 & -3\epsilon+\sigma \\ 0 & 3\epsilon+\sigma & 1 \end{bmatrix} m_U \; ; \quad L = \begin{bmatrix} 0 & -3\epsilon'+\eta' & 0 \\ 3\epsilon'+\eta' & 0 & -3\epsilon+\eta \\ 0 & 3\epsilon+\eta & 1 \end{bmatrix} m_D$$

$$M_\nu^R = \begin{bmatrix} x & 0 & z \\ 0 & 0 & y \\ z & y & 1 \end{bmatrix} M_R$$

$$\begin{aligned} \mathcal{L}_{Yuk} = \Big(& h_{33}\, 16_3 16_3 10_H + \frac{a_{23}}{M} 16_2 16_3 10_H 45_H + \frac{g_{23}}{M} 16_2 16_3 16_H 16_H \\ & + h_{23}\, 16_2 16_3 10_H + \frac{g_{12}}{M} 16_1 16_2 16_H 16_H + \frac{a_{12}}{M} 16_1 16_2 10_H 45_H \Big) \\ & + \left(16_3 16_3 \overline{16}_H \overline{16}_H + 16_2 16_3 \overline{16}_H \overline{16}_H + 16_1 16_1 \overline{16}_H \overline{16}_H + 16_1 16_3 \overline{16}_H \overline{16}_H \right) \end{aligned}$$

PREDICTIONS

$$m_b^\circ \simeq m_\tau^\circ \Rightarrow m_b(m_b) \simeq 4.9 \text{ GeV}$$

$$m_s(1 \text{ GeV}) \simeq 116 \text{ MeV}$$

$$m_d(1 \text{ GeV}) \simeq 8 \text{ MeV}$$

$$\theta_c \simeq \left| \sqrt{m_d/m_s} - e^{i\phi} \sqrt{m_u/m_c} \right|$$

$$\left| \frac{V_{ub}}{V_{cb}} \right| \simeq \sqrt{m_u/m_c} \simeq 0.07$$

$$\sin^2 2\theta_{\mu\tau} = (0.96 - 0.81) \quad \text{FOR}$$

$$m_{\nu_\mu}/m_{\nu_\tau} = (1/10 - 1/30)$$

$$\theta_{e\mu} \simeq (0.85)\sqrt{\frac{m_e}{m_\mu}} \cos\theta_{\mu\tau} \simeq 0.04$$

$$\theta_{e\tau} \simeq 0.0034$$

DOUBLET-TRIPLET SPLITTING

$$W_{DT} = \lambda\, 10_H\, 45_H\, 10'_H + M_{10}\, {10'_H}^2 + \lambda'\, \overline{16}_H\, \overline{16}_H\, 10_H + M_{16}\, 16_H\, \overline{16}_H$$

$$\left(\bar{5}_{10_H} \;\; \bar{5}_{10'_H} \;\; \bar{5}_{16_H}\right) \begin{bmatrix} 0 & \lambda\langle 45_H\rangle & \lambda'\langle \overline{16}_H\rangle \\ -\lambda\langle 45_H\rangle & M_{10} & 0 \\ 0 & 0 & M_{16} \end{bmatrix} \begin{pmatrix} 5_{10_H} \\ 5_{10'_H} \\ 5_{\overline{16}_H} \end{pmatrix}$$

(Dimopoulos, Wilczek)

$$\langle 45_H\rangle = \mathrm{diag.}\,(a \;\; a \;\; a \,\vdots\, 0 \;\; 0) \times \tau_2$$

ALL COLOR-TRIPLETS BECOME HEAVY

$$\left\{ \begin{array}{l} H_u = 10_u \\ H_d = \cos\gamma\; 10_d + \sin\gamma\; 16_d \end{array} \right\}$$ LIGHT MSSM FIELDS

$$\tan\gamma = \lambda'\langle \overline{16}_H\rangle / M_{16}$$

$$\tan\beta \tan\gamma = \frac{m_t}{m_b}$$

PROTON DECAY AMPLITUDE

$$\mathcal{A} \propto \frac{1}{M_{eff}}, \qquad M_{eff} = \frac{\lambda^2 \langle 45_H \rangle^2}{M_{10}}$$

$M_{eff} \approx 10^{18}$ GeV ALLOWED, e.g., IF M_{10} IS SOMEWHAT BELOW GUT SCALE.

M_{eff} APPEARS IN THRESHOLD CORRECTION TO $\alpha_s(m_Z)$:

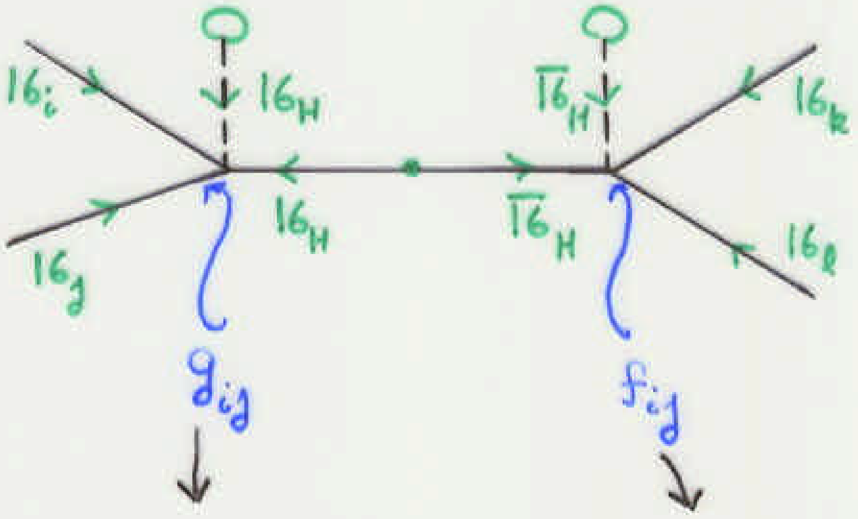
$$\Delta\alpha_3(m_Z)\Big|_{DT} = \frac{[\alpha_3(m_Z)]^2}{2\pi}\left(\frac{9}{7}\right) \ln\left\{\frac{M_{eff}\cos\gamma}{M_U}\right\}$$

FOR $\cos\gamma \ll 1$ $(\tan\beta \sim \mathcal{O}(1))$

$M_{eff} \sim 10^{18}$ GeV ALLOWED

DOUBLETS ARE NATURALLY LIGHT-WITHOUT FINE-TUNING

NEW PROTON DECAY OPERATOR LINKED TO NEUTRINO MASSES



INDUCES CKM
QUARK MIXING

INDUCES
ν_R MAJORANA MASSES

NEW ν-MASS RELATED OPERATOR LEADS TO PROMINENCE OF

$$p \to \mu^+ K^0$$

$$\frac{\Gamma(p \to \mu^+ K^0)}{\Gamma(p \to \bar{\nu} K^+)} \simeq (10-50)\,\%$$

$$\begin{aligned}
\hat{A}[(ud)(s\nu_\tau)] \simeq\ & M_{eff}^{-1} h_t^2 \big[1.9\times10^{-5}\eta_{cd}\eta_{ts}\eta_{\epsilon'} - 9.0\times10^{-6}\eta_{cd}\eta_{cb}\eta_{\epsilon'} \\
& - 6.1\times10^{-6}\eta_{td}\eta_{ts}\eta_{cb}\eta_{\epsilon'} + 4.8\times10^{-6}\eta_{ts} - 2.5\times10^{-6}\eta_{cs} \\
& + 2.1\times10^{-6}\eta_{td}\eta_{\eta'} + 3.0\times10^{-6}\eta_{cd}\eta_{ts}\eta_{\eta'} \\
& + 2.2\times10^{-6}\eta_{cd}\eta_{cb}\eta_{\eta'} \big] + (M_{16}\tan\gamma)^{-1} h_t \hat{f}_{33} \times \\
& \big[3.0\times10^{-7}\eta_{cd}\eta_{ts}\eta_{\epsilon'} + 6.0\times10^{-7}\eta_{td}\eta_{ts}\eta_{cb}\eta_{\epsilon'} \\
& + 4.3\times10^{-7}\eta_{td}\eta_{ts}\eta_{cb}\eta_{\eta'} + 1.5\times10^{-7}\eta_{td}\eta_{\eta'} \\
& + 2.3\times10^{-7}\eta_{cd}\eta_{ts}\eta_{\eta'} - 0.0411\eta_{cb}x + 3.1\times10^{-5}y\,\eta_{cd}\eta_{\epsilon'} \\
& + 2.2\times10^{-5}y\,\eta_{cd}\eta_{ts}\eta_{cs}\eta_{\epsilon'} + 1.1\times10^{-5}\eta_{td}\eta_{cb}\eta_{\eta'}y \\
& + 1.6\times10^{-5}\eta_{cd}\eta_{ts}\eta_{cs}\eta_{\eta'}y + 1.1\times10^{-5}\eta_{cd}\eta_{\eta'}y \\
& + z\{ -2.47\times10^{-4}\eta_{td}\eta_{cs} - 1.28\times10^{-4}\eta_{cd} \\
& \quad + 9.94\times10^{-5}\eta_{ts}\eta_{cs}\eta_{\epsilon'} + 7.23\times10^{-5}\eta_{ts}\eta_{cb}\eta_{\eta'} \} \big]
\end{aligned}$$

A DETAILED ANALYSIS, ALLOWING FOR REASONABLE UNCERTAINTIES IN SUSY PARAMETERS YIELDS

$$\boxed{\Gamma^{-1}(p \to \bar{\nu} K^{+}) \lesssim 7 \times 10^{33}\ \text{yrs}}$$

FOR $m_{squark} \simeq 1.4$ TeV

$\beta_H \simeq 0.006\ \text{GeV}^3$

$Br\,(p \to \mu^{+} K^{0}) \simeq (10-50)\,\%$

CONCLUSIONS

- SUSY SO(10) IS AN ATTRACTIVE FRAMEWORK TO ADDRESS NEUTRINO MASSES & MIXINGS
- PROTON DECAY LIMITS PUT SIGNIFICANT STRESS ON THE FRAMEWORK. $p \to \bar{\nu} K^+$ MUST BE SEEN WITH $\tau_p \lesssim 7 \cdot 10^{33}$ yr, OR THE FRAMEWORK FAILS.
- IT IS HIGHLY DESIRABLE TO IMPROVE CURRENT LIMITS BY A FACTOR OF (20-100) AT A "NEXT GENERATION NUCLEON DECAY AND NEUTRINO DETECTOR"