Proton decay and grand unification

Goran Senjanović

ICTP

C. Aulakh, B. Bajc, P. Filevez Pérez, A. Melfo,

M. Nemevšek, A. Rašin, F. Vissani

review and references:

Fileviez-Pérez, Nath '06

PLAN

- the Holy Grail: search for 'THE' minimal predictive theory

  d=4 - purely phenomenological

  mainly SU(5) - both ordinary and supersymmetric $\longrightarrow$ SO(10)

  no such theory emerged

- generic features of large GUT scale desert picture vs low energy source of proton decay

PROTON RATHER STABLE

τ_p much bigger than τ_n, τ_μ

Feel it in your bones: roughly $\tau_p \geq 10^{16}$ year

otherwise killed by radiation

10^{27} protons/kg

let $\tau_p = 10^x$ year

10^{27-x} protons decay per year, with 10^{30-x} MeV/year radiated

lethal limit: 10^{14} MeV/year

Goldhaber, fifties?

Proton stability

BARYON NUMBER

Weyl '29

Stuckelberg '39

Wigner '49

$\longrightarrow$ DOGMA

Reines, Cowan, Goldhaber, Phys. Rev. 96, 1157 (1954)

In view of the fundamental nature of such an assumption, it seemed of interest to investigate the extent to which the stability of nucleons could be experimentally demonstrated."

neutrino detectors

$$\tau_p \geq 10^{26} \quad \text{yr}$$

THE ONLY GOOD (GLOBAL) SYMMETRY IS A BROKEN (GLOBAL) SYMMETRY

B not unbroken gauge symmetry - unless $g_B \leq (10^{-20} - 10^{-19})$

Charge conservation and the lifetime of the electron?

$$\tau_e \geq 10^{26}\ \text{yr} \quad (e \to \nu + \gamma)$$

Moe, Reines '65

proton decay ⇐ THEORY

GRAND UNIFICATION

Pati, Salam '73, '74

Georgi, Glashow '74

- charge quantization
- gauge coupling unification

predicts

- magnetic monopoles
- proton decay

Goldhaber: *many rushed underground*

Proton decay rush

calorimeter

- Kolar Gold Field - Kolar district (Kamataka, India)
- NUSEX - Mont Blanc (Alps, France)
- FREJUS - Frejus tunnel (Alps, France)
- SOUDAN- Soudan underground mine (Minnesota, US)

Cherenkov

- IMB - Morton salt mine (Ohio, US)
- Kamiokande - Mozumi mine (Hida, Japan) →

  Super-Kamiokande → atmospheric neutrino oscillations

Channel	$\tau_p(10^{33}$ years)
• $p \to e^+\pi^0$	8.2
• $p \to \mu^+\pi^0$	6.6
• $p \to \mu^+K^0$	1.3
• $p \to e^+K^0$	1.0
• $p \to \nu K^+$	2.3 (1.5?)
• $n \to e^+K^-$	0.02
• $n \to e^-K^+$	0.03

important to improve $\Rightarrow$ indication of low scale

Minimal SU(5)

Georgi, Glashow '74

caused the underground rush: fast proton decay $\tau_p \simeq 10^{30}$ yr

Higgs: 24_H (GUT Higgs)+5_H (SM Higgs)

matter: $3(10_F + \overline{5}_F)$

asymmetric matter, fine tuning (D-T splitting) - but simple and predictive

$$5_H \equiv \begin{pmatrix} T & D \end{pmatrix}$$

T color triplet, SU(2) singlet $(3_C, 1_W, 2/3)$

D usual Higgs doublet $(1_\mathrm{C}, 2_\mathrm{W}, 1)$

T- proton decay→ heavy

D-T splitting

if NO higher dimensional operators:

- D and T couplings connected ⇒ p decay branching ratios predicated
- bad mass relations: $m_d = m_e$

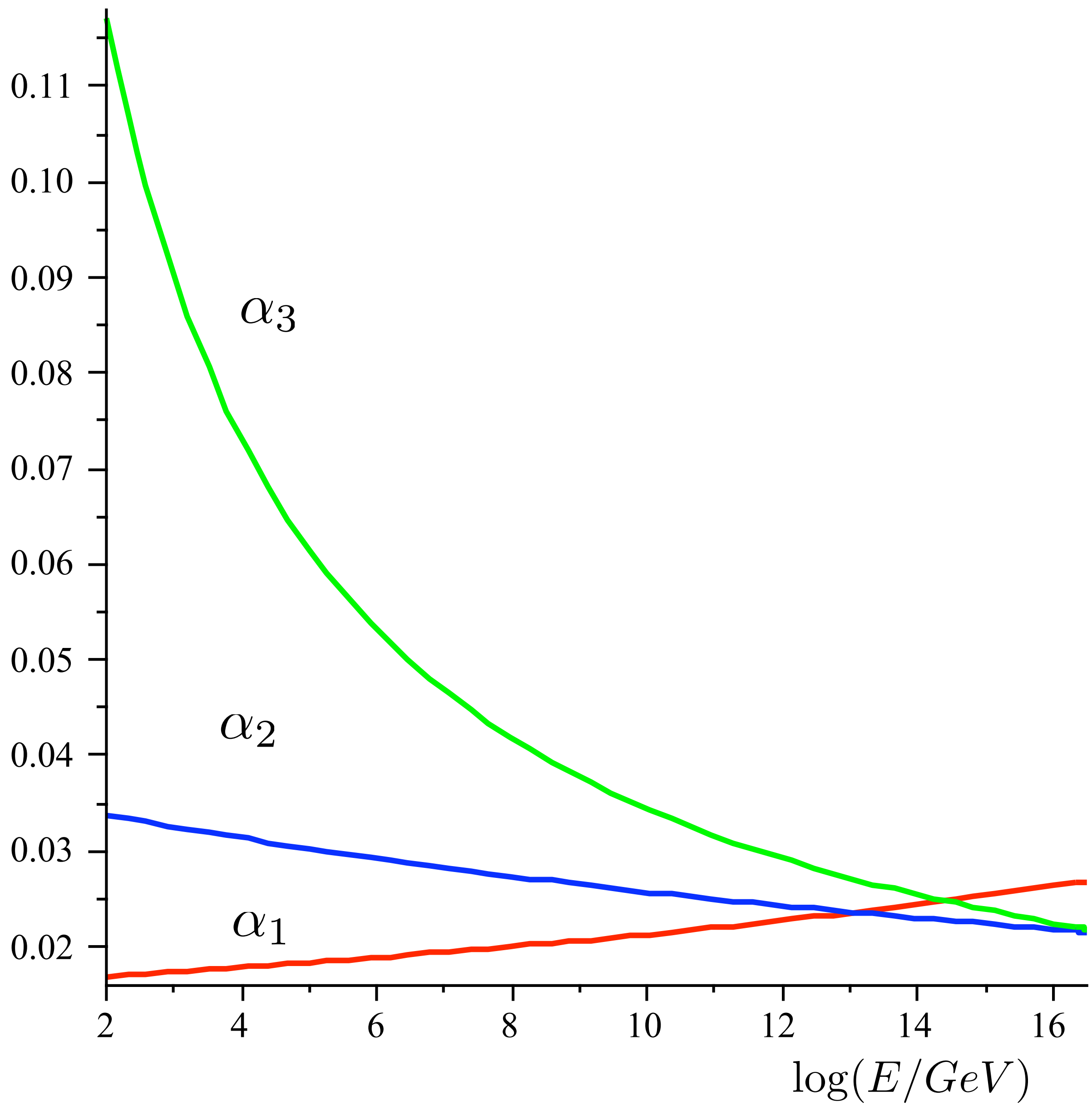
RULED OUT

- gauge couplings do not unify

  even with thresholds:

$$24_H = (8_c, 1_W) + (1_c, 3_W) + (1_c, 1_W) + \text{“goldstones”}$$

- neutrinos massless (as in the SM)


0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
2
4
6
8
10
12
14
16
α_3
α_2
α_1
$\log(E/GeV)$

Minimal extensions that cure both problems:

- 15_H: type II seesaw

$$15_H = (1_C, 3_W) + (6_C, 1_W) + [(3_C, 2_W) - leptoquarks]$$

possibly light leptoquarks

Doršner, Fileviez Pérez '05

- 24_F: type I + III seesaw

PREDICTIVE

$$24_F = (8_C, 1_W) + (1_C, 3_W) + (1_C, 1_W) + (3_C, 2_W) + (\bar{3}, 2_W)$$

less than TeV light triplet fermion - LHC

decays violate lepton number and probe neutrino mass matrix

Bajc, G.S. '06

Bajc, Nemevšek, G.S. '07

Arhrib, Bajc, Ghosh, Han, Huang, Puljak, G.S. '09

PROTON DECAY

- both cases 'fast' proton decay: $\tau_p \leq 10^{35}$ yr

- **B-L :** accidental symmetry

proton decays into an anti-lepton

underground rush continues

MINIMAL SUPERSYMMETRIC SU(5)

Dimopoulos, Georgi '81

- low energy supersymmetry $\Leftarrow$ stabilize hierarchy

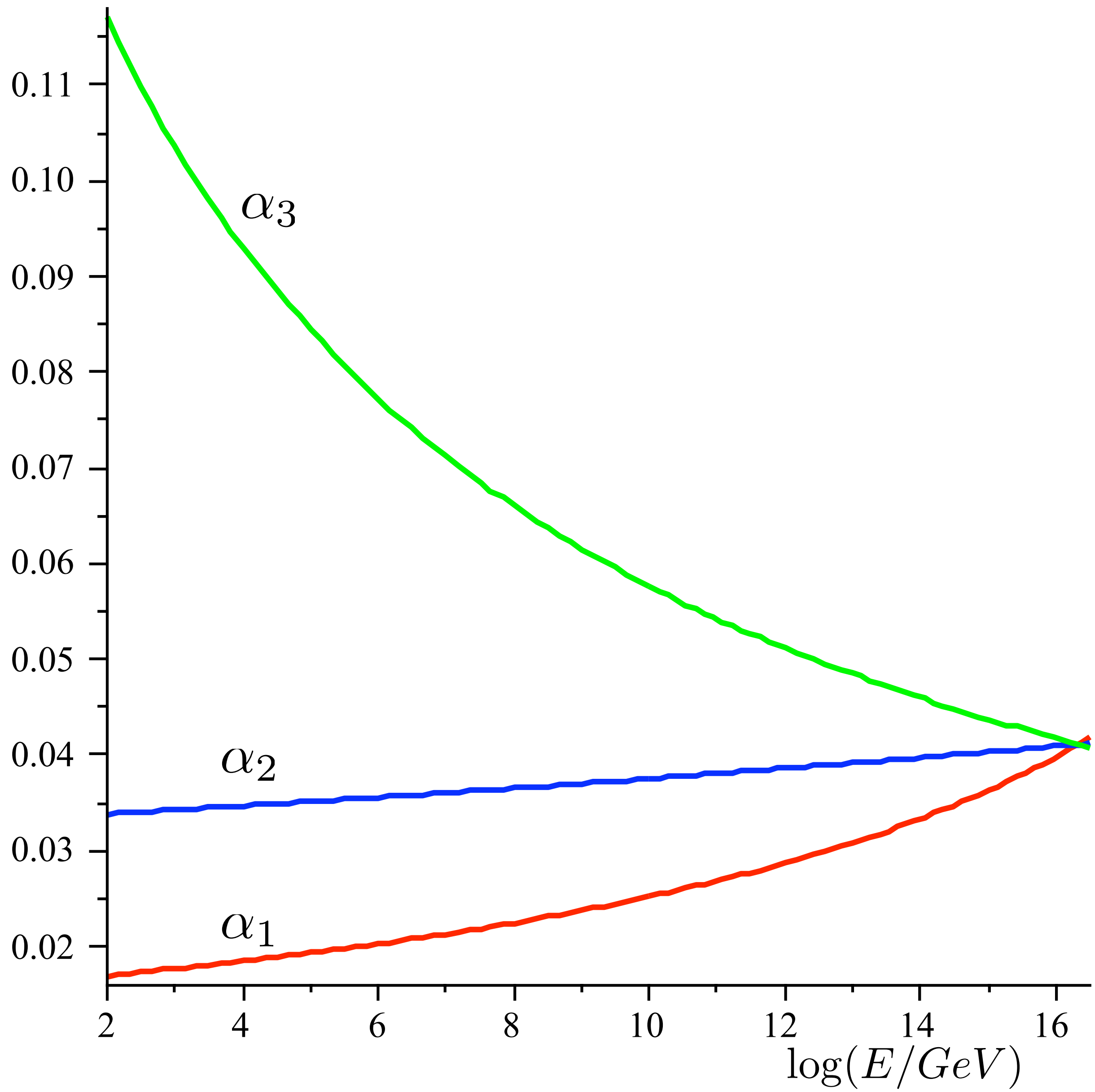
- $\Rightarrow \sin^2\theta_W = 0.23$ - great success when confirmed by LEP

Ibanez, Ross '80

Dimopulos, Rabi, Wilczek '80

Einhorn, Jones '81

Marciano, G.S. '81


0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
α_3
α_2
α_1
2
4
6
8
10
12
14
16
$\log(E/GeV)$

supersymmetric unification $\longrightarrow$ heavy top

Marciano, G.S. '81

'81 - experiment: $\sin^2\theta_W = 0.21$ for $\rho \simeq 1 \longrightarrow$ grows with ρ

Needed: $\rho > 1 \Rightarrow$

loops $\Rightarrow$

large $Y_t \Rightarrow$

heavy top: $m_t \simeq 200$ GeV

$M_{GUT} \simeq 10^{16}$ GeV (? see below)

$\boxed{\tau_p(d=6) \simeq 10^{35\pm1} \text{ yr}}$ Seemed out of reach

New contribution:

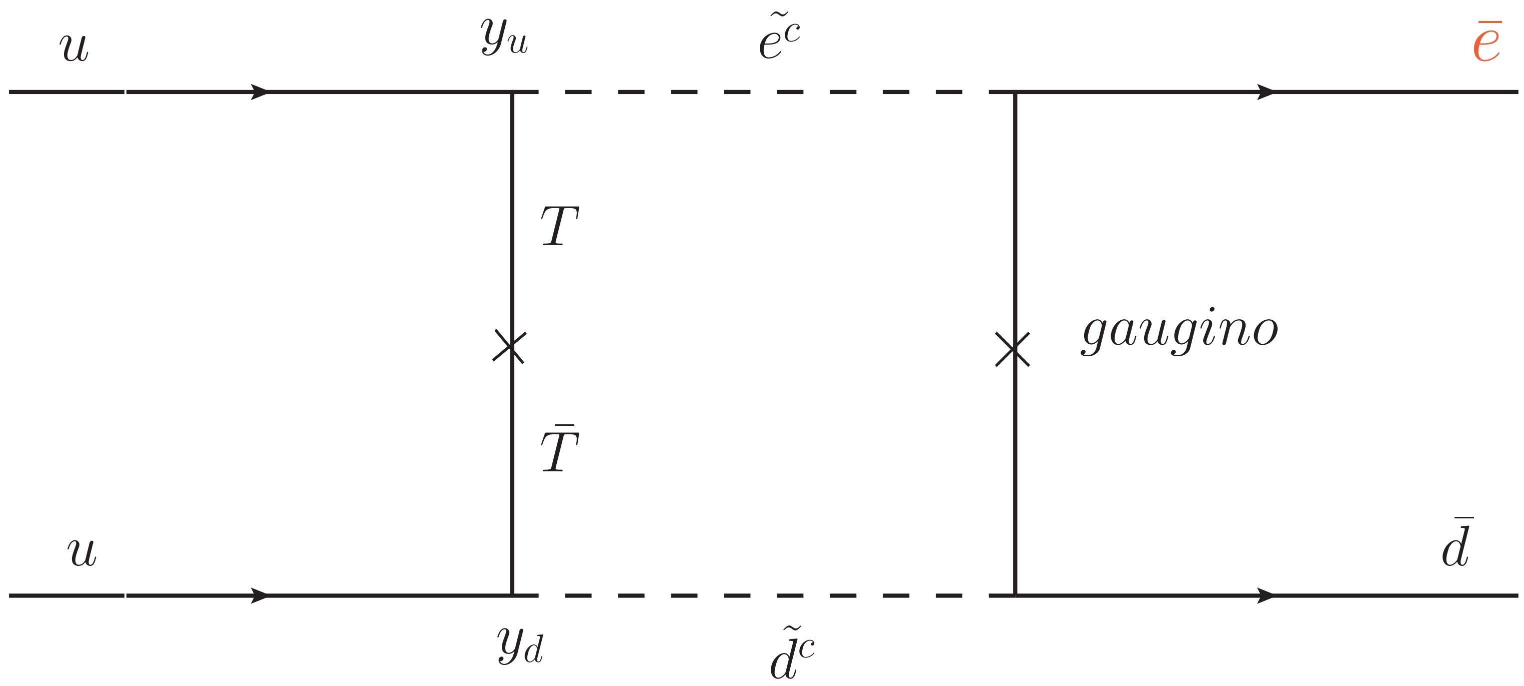
$d = 5$ operators

through the exchange of heavy color triplet Higgsino (T and $\bar{T}$)

$$\frac{1}{M_T} q q \tilde{q} \tilde{e}$$

Weinberg '82

Sakai, Yanagida '82


u
y_u
$\tilde{e}^c$
$\bar{e}$
T
gaugino
$\bar{T}$
u
$\bar{d}$
y_d
$\tilde{d}^c$

$G_T\, q\, q\, q\, \ell$ B-L conserved as before

$$G_T \simeq \frac{\alpha}{4\pi} y_u\, y_d \frac{m_{\text{gaugino}}}{M_T m_{\tilde{f}}^2} \simeq 10^{-30}\ \text{GeV}^{-2}$$

for $y_u \simeq y_d \simeq 10^{-4}$

$m_{\text{gaugino}} \simeq 100$ GeV $m_{\tilde{f}} \simeq$TeV

$M_T \simeq 10^{16}$ GeV

$\Rightarrow$ $\boxed{\tau_p(d=5) \simeq 10^{30-31}\ \text{yr}}$

RULED OUT!?

- uncertainties: $\tilde{f}$ spectrum and mixings

Bajc, Fileviez-Pérez, G.S. '02

- wrong mass relations: $m_e = m_d$

correct mass relations

$\rightarrow$ lose connection between D and T couplings

Diaz-Cruz, Murayama, Pierce '00

Babu, Bajc, Dorsner, Enkhbat, G.S. '09

- cure for bad mass relations: higher dimensional operators

Ellis, Gaillard '79

$\longrightarrow$ increase M_{GUT}

Bachas, Fabre, Yanagida '96

$\longrightarrow$ increase M_T

Bajc, Fileviez-Pérez, G.S. '02

$$24_H = (8_c, 1_W) + (1_c, 3_W) + (1_c, 1_W) + \text{“goldstones”}$$

$\Rightarrow$ split the triplet and octet masses: threshold effects

$$\left.\begin{array}{l} M_{GUT} = M_{GUT}^0 \left(\frac{M_{GUT}^0}{2m_8}\right)^{1/2} \\ M_T = M_T^0 \left(\frac{m_3}{m_8}\right)^{5/2} \end{array}\right\} M_{GUT}^0 \simeq 10^{16} \text{ GeV}$$

$$M_T^0 \simeq 3 \times 10^{15} \text{ GeV}$$

Murayama, Pierce '01

- $d = 4 \Rightarrow m_3 = 4m_8$

$$M_T = 32 M_T^0 \simeq 10^{17} \text{ GeV} \simeq M_{GUT} \; (m_8 \simeq 10^{15} \text{ GeV})$$

$$\boxed{\tau_p \simeq 10^3 \tau_p^0 (d=5) \simeq 10^{33-34} \text{ yr}}$$

Bajc, Fileviez-Pérez, G.S. '02

Minimal Supersymmetric SU(5)

VIABLE

"Prediction": $p \to K^+ \bar{\nu}_\mu$ dominant

B-L accidental symmetry in proton decay: *qqql*

? ? ?

$R(p)$ **must be broken** $\Leftarrow$ neutrino masses

Bajc, Chun, Enkhbat, G.S. '09

$$...+ \lambda_1 \, u^c \, d^c \, d^c + \lambda_2 \, q \, \ell \, d^c$$

$$\Longrightarrow \tilde{d}^c \text{ mediates } d = 6 \text{ proton decay}$$

$$\Longrightarrow \lambda_1 \, \lambda_2 \leq 10^{-25} \; (=?)$$

possible decay: $n \to e + K^+$

B + L conserving

B - L violating

Vissani '96

$R(p)$ breaking $\Longrightarrow$ unstable neutralino

- $\Delta L \neq 0$ at colliders

- neutrino gaugino mixing

$$\Theta_{\nu\,\text{gaugino}} \simeq \sqrt{\frac{m_\nu}{M_{\text{gaugino}}}}$$

- only possible DM in the minimal model: gravitino

$$3/2 \to \gamma + \nu$$

$$\Gamma(3/2 \to \gamma\nu) \quad = \quad \frac{1}{32\pi}\frac{m_{3/2}^3}{M_{Pl}^2}\Theta^2_{\nu\,\mathrm{gaugino}} \simeq \frac{1}{32\pi}\frac{m_{3/2}^3}{M_{Pl}^2}\frac{m_\nu}{M_{\mathrm{gaugino}}}$$
$$\leq 10^{-50}\ \mathrm{GeV} \qquad (\tau \geq 10^{26} sec)$$

$$\Rightarrow \boxed{m_{3/2} \leq 10\ \mathrm{GeV}}$$

for more possibilities beyond MSSM

Buchmuller SUSY09

SO(10)

Georgi '74 ; Fritzch, Minkowski '74

- Unifies a fermion family: 16_F
- Right-handed neutrino: N
- $M_N \gg M_W$: see-saw
- Supersymmetry:

  $R(p)$ = gauge symmetry

Mohapatra '86

- Renormalizable version

  $R(p)$ remains exact $\rightarrow$ LSP stable $\rightarrow$ DM

Aulakh, Benakli, G.S. '96 ; Aulakh et al. *'00*

More Higgs

$$10_H + (126_H \rightarrow \text{N mass})$$

Deshpande, Keith, Pal '93

Acampora et al. *'94*

Bajc, Melfo, G.S., Vissani '05

Bertolini, Di Luzio, Malinsky '09

NO realistic predictive model

- **Supersymmetric** SO(10)

Aulakh, Mohapatra '82

Clark, Kuo, Nakagawa '82

Babu, Mohapatra '92

Bajc, G.S., Vissani '02

Aulakh, Bajc, Melfo, G.S., Vissani '03

$10_H + 126_H$ (holomorphic) $\Rightarrow$ predictive

(no higher dimensional operators)

after initial success...

tension between neutrino mass and proton decay when pinned down precisely

seems to work only with $\tilde{m} \gg M_W$ (split supersymmetry)

$\Rightarrow d = 6$ p-decay with predicted branching ratios and fast overall decay (borderline)

Bajc, Doršner, Nemevšek '08

example of how model may decide on the low energy effective theory

Bajc, G.S. '04

	Partial mean life (10^{33} years)		
p decay modes	Model predictions	Lifetime bounds	Fraction (Γ_i/Γ)
$p \to \pi^0 e^+$	12.1	> 8.2	44.3 %
$p \to \pi^0 \mu^+$	518.7	> 6.6	1.0 %
$p \to K^0 e^+$	3277.2	> 1.0	0.2 %
$p \to K^0 \mu^+$	113.4	> 1.3	4.7 %
$p \to \eta e^+$	1765.6	$> .313$	0.3 %
$p \to \eta \mu^+$	75499.3	$> .126$	0.007 %
$p \to K^+ \bar{\nu}$	1190.2	> 2.3	0.5%
$p \to \pi^+ \bar{\nu}$	10.9	$> .025$	49.1 %

$$126_H \to 16_H$$

- breaks R(p)

Babu, Barr, Raby, Lucas, Dermisek, Mohapatra, Berezhiani, Nesti, Pati, Tavartkiladze, Wilczek...

GUT not sufficient, needs physics beyond. Some rather detailed studies of textures and sfermion spectrum

Babu SUSY09

no consensus on the simple predictive theory

GUT: generic predictions ?

$M_{GUT} \gg M_W \Rightarrow$ effective operator expansion

SM symmetry: $SU(3) \times SU(2) \times U(1)$

expansion in M_W/M_B or m_p/M_B where M_B is the scale responsible for p decay

(GUT with desert picture: $M_B = M_{GUT}$)

- leading $d = 6$: only 4 operators

$O_1 = (u_R\, d_R)\,(q_L\, \ell_L)$ $\qquad$ $O_2 = (q_L\, q_L)\,(u_R\, e_R)$

gauge boson

$O_3 = (q_L\, q_L)\,(q_L\, \ell_L)$ $\qquad$ $O_4 = (u_R\, d_R)\,(u_R\, e_R)$

scalar

Weinberg '79; Wilczek, Zee '79; Abbott, Wise '80

B-L automatic accidental

- Isospin relations

$$\Gamma(p \to \ell_R^+ \pi^0) = \frac{1}{2}\Gamma(n \to \ell_R^+ \pi^-) = \frac{1}{2}\Gamma(p \to \bar{\nu}\pi^+) = \Gamma(n \to \bar{\nu}\,\pi^0)$$

$$\Gamma(p \to \ell_L^+ \pi^0) = \tfrac{1}{2}\Gamma(n \to \ell_L^+ \pi^-)$$

- $\bar{s}$ goes out

$\Rightarrow p \to K^+ \bar{\nu}$ $\quad$ $n \not\to K^+ \ell$ $\quad$ $n \not\to K^- \ell^+$

and more (not completely generic)

Weinberg '81

Weldon, Zee '81

Fileviez Pérez '04

R(p) violation

$$\boxed{n \to K^+ e}$$

Vissani '96

$$d\, s\, d\, \bar{\ell}\, \langle H \rangle / \tilde{m}^3$$

in GUT: $\tilde{m} \to M_{GUT} \to$ suppression : M_W / M_{GUT}

also $\boxed{n \not\to \pi^+ e}$

MESSAGE

$$n \to K^+ \, e \qquad\qquad n \to K^- \, e^+$$

$\Rightarrow$ low energy source of proton decay

limits roughly 10^{31} yr

$\longrightarrow$

urge experimentalists to improve them

Proton decay: matrix elements

non-relativistic quark model, bag model, chiral lagrangians, lattice

Ioffe '81

Tomozawa '82

Krasnikov, Pivovarov, Tavkhelidze '82

Meljanac, Palle, Picek, Tadic '82

Donoghue, Golowich '82

Claudson, Hall, Wise '82

Brodsky et al. *'84*

Gavela et al. *'89*

Tsutsui et al. *'04*

Claudson, Hall, Wise '82

- **lattice**

  still in progress

  Aoki, Dawson, Noaki, Soni '06

- **chiral langrangians + lattice**

  leading terms in (momentum/GeV) expansion

  Claudson, Hall, Wise '82

  Aoki et al '08

two coefficients: α (Vector Meson) and β (Scalar Meson):

Lattice

$$\alpha = -\ 0.0112 \pm 0.0012(\text{stat}) \pm 0.0022(\text{syst}) \ \ \text{GeV}^3$$

$$\beta = 0.0120 \pm 0.0013(\text{stat}) \pm 0.0023(\text{syst}) \ \ \text{GeV}^3$$

Aoki et al '08

works best for soft pions but here momentum up to 500 MeV.
Higher orders?

Grand Unification:

- NO complete accepted theory
- most models: $\tau_p \leq 10^{35}$ yr

  especially SUSY
- minimal SU(5) ruled out- minimal extension LHC physics
- minimal SUSY SU(5) viable $\rightarrow$ gravitino unstable dark matter

- test of GUT desert picture $\boxed{n \not\to K^+ \ell}$ $\boxed{n \not\to K^- \ell^+}$

  limits 10^{31} yr

- above decays - low energy physics, below TeV

  connection between p decay and LHC

New generation of experiments badly needed

Proposed experiments

Cherenkov detector - MEGATON

- HYPER-Kamiokande
- 3M -(Megaton, Modular, Multipurpose)
  Homestake - DUSEL (Deep Underground Science and Engineering Lab)
- MEMPHYS - (MEgaton Mass PHYSics)
  Fréjus - LAGUNA (Large Apparatus Grand Unification and Neutrino Astrophysics) project

$$p \longrightarrow \ell^+ \pi^0$$

Liquid Argon Detector - 100 kT

- LANNDD (Liquid Argon Neutrino Nucleon Decay Detector)
  Homestake - DUSEL?
- GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment)
  Europe - Laguna

Liquid scintillator - 50 kT

- LENA (Low Energy Neutrino Astronomy)
  Europe - Laguna

$$p \to \bar{\nu} K^+$$

should reach 10^{35} yr in 10-20 years!?

started: proton decay kills by radiation

Recommended limits:

EU/Switzerland: 10^{11} Mev/yr

about two CT scans

LAST BUT NOT LEAST - be careful