PROTON DECAY

IN

MINIMAL GRAND UNIFIED THEORIES

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GRAND UNIFICATION

\[ G \cong SU(2) \times U(1) \times SU(3)_c \]

\[ \uparrow \quad \text{simple} \]

\[ \downarrow \]

- MAGNETIC MONPOLES
- PROTON DECAY

PREDICTIONS?

- \( M_m = \frac{M_{GUT}}{8} \); search not very sensitive to a precise value of \( M_m \)

MACRO (Gran Sasso):

- \( \text{flux} \leq 10^{-15} \text{ cm}^{-2} \text{sec} \) (but expected much smaller flux)

TROUBLE: depends on cosmology

Typical: hard to predict or too few (inflation)
GENERIC PREDICTION (SUSY and NON SUSY)

d = 6 through new heavy gauge bosons (X)

BUT: \[ T_Y \propto H X_4 \Rightarrow \text{NEED PRECISE DETERMINATION OF } M_X \]

POSSIBLE?

THE MINIMAL THEORY: MINIMAL SU(5)

at the renormalizable level (as example)

(NOT REALISTIC: \( m_Y = 0 \)

\( m_S = m_R, m_D = m_e \) \text{ at } M_GUT)

Needs SUSY (or split SUSY) for gauge coupling unification
MINIMAL SUSY SU(5)

\[ W_H = \lambda \mathfrak{tr} Z g^3 + m_{24} \mathfrak{tr} Z g^2 \]
\[ + (\mu + \alpha Z g) \bar{5}_H 5_H \]
\[ \downarrow \]
\[ \delta_c, 3_w \text{ in } Z g_H \quad \text{or} \quad m^3 = m_{\bar{h}} = \lambda \langle 24_H \rangle \]
\[ \text{color octet} \quad 1/2 \text{b} \text{b} \text{ triplet} \]

\[ \bar{T}, \bar{T} \text{ in } 5_H, \bar{5}_H \quad m_T = \alpha \langle 24_H \rangle \]
\[ \text{color triplet} \]

Four unknowns: \( m_{\Sigma}, m_T, M_X, \alpha \)

(low energy susy)

3 equations: \( \alpha_i \) running \((i = 1, 2, 3)\)

Cannot determine everything
\[ M_X \ 
\frac{w^2}{M_X} = M_{\text{cut}}^3, \quad M_{\text{cut}} = 10^{16} \text{ GeV} \]

**arbitrary**: \( w^2 = \frac{1}{9} M_X \)

Yukawa (self-renormalizable) can be naturally small

Only if \( M_X = M_Z \Rightarrow M_X = 10^{16} \text{ GeV} \quad T_P = 10^{35} \text{ y} \)

E.g. \( M_Z = 10^{16} \text{ GeV} \Rightarrow M_X = 10^{17} \text{ GeV} \quad T_P = 10^4 \text{ y} \)

\[ d = 6 \text{ proton decay rate uncertain} \]

However \( m_T \) calculable: \( m_T = 3 \times 10^{15} \text{ GeV} \)

\[ T_P (d=5) < 10^{32} \text{ y} \quad \text{Murray, Pierce} \]

Minimal SUSY SU(5) ruled out!

However, sfermion mixing uncertainties \( \text{not clear} \)

\( \text{Bajc, Fileviez, Perez, et al.} \)
Worse: needs $d=6$ operators in Weylawa
(or a change of the structure of the theory)
in order to correct bad mass relations

if $\lambda$ small $\Rightarrow d=4$ in $W_H$

$$\Delta W_H = \alpha \frac{(\text{Tr} \, Z_H^2)^2 + \beta \text{Tr} \, Z_H^4}{M_p c}$$

$m_3 = 4 m_8$

$$m_T = m_T^0 \left( \frac{m_3}{m_8} \right)^{5/2}$$

renormalizable level result ($m_3 = m_8$)
cited before: $m_T^0 = 2 \times 10^{15}$ GeV

$m_T \rightarrow 10^{17}$ GeV

$\Rightarrow \tau_T = 10^2 \tau_T^0 - \text{consistent with experiment}$
Possibility: Split supersymmetry

Sfermions heavy & complete

Representations, unification OK

Arhan, Hemed,
Dimopoulos

\[ d = 5 \text{ suppressed,} \quad (\text{strings:} \text{ Klebanov, Witten}) \]

\[ d = 6 \text{ back in the game} \]

\[ m_{\tilde{\nu}} \text{ close to Higgs} \]

\[ \text{uncertainties in } \bar{\nu}_p \times M_{\nu}^4 \text{ (even if} \]

\[ m_{\nu} \text{ close to Hoot}) \]

• also, mixing angles uncertainties

• recent studies:

Ferreira, Peres

Donini, Ferreira, Peres

Desperately seeking new

Generation of p decay experiments
Assumed: $d=4$ p decay forbidden

\[ \downarrow \]

R-parity

\[ \uparrow \]

Exact?

\[ \uparrow \]

Yes, in $SO(10)$

What about $\mu \nu \neq 0$?

$SU(5)$ not a good theory of $\mu \nu$

(Gr singlet, or new Higgs)

\[ \downarrow \]

$SO(10)$ natural

(with Pati-Salam)
SO(10)

- Contains SU(5) and PS: both merits
- Truly unified: 1 gauge coupling
- 1 family 1 representation:
  \[ 16 = (\mathbf{5}, \mathbf{f}^c)_L = (10 + \mathbf{\bar{5}} + 1) \]
  \[ \mathbf{f}^c \]
- Charge conjugation \( f \to f^c \): gauge symmetry
- See-saw natural (both I and II)
- Supersymmetry at low E: R-parity exact
  \( \Rightarrow \) LSP dark matter
- No SUSY (or higher): MR inner scale
  \( \sim 10^{10} - 10^{16} \text{ GeV} \)
  Ideal for M3
  \( (~10^{12} \text{ GeV}) \)
If fine tuning accepted

\[ \Rightarrow \]

No need for supersymmetry

But:

- Unification?
- Dark matter?

Gauge coupling unification:

No need for $SU(14)$ in $SO(10)$
Gauge Coupling Unification

$\alpha$

$SU(3)$

$SU(2)$

$U(1)$

$10^{16}$ GeV E

SM: Does not work

(LOW ENERGY)

SUPERSYMMETRY (OR SPLIT SUPERSYMMETRY):

CHANGES $U(1)$ so all three meet at $\sim 10^{16}$ GeV

(little miracle: 2-3 coupling does not depend on SUSY)

(LOW E) SUSY: single step breaking preferred
susy +
single step unification:

\[ \sin^2 \theta_w = 0.23 \]

\[ m_t \approx 200 \text{ GeV} \]

(in order to have \( p = \frac{H_w^2}{H^2_w \omega^2 \omega} \neq 1 \))

\[ \text{BUT} \]

\[ \text{WITHOUT SUPERSYMMETRY MUST SLOW DOWN } U(1) \text{ RUNNING} \]

\[ U(1) = SU(2)_R \times U(1)_{B-L} \]

\[ \text{non-abelian, asympt. free} \]

\[ M_R \ll M_{HUT} \]

\[ \text{running: } M_R \approx 10^{12} - 10^{14} \text{ GeV} \text{ fits perfectly for } M_W \]

(see text)
\( SO(10) \) works with SUSY,
SPLIT SUSY AND
No SUSY AT ALL

- Symmetry Breaking

1. SMALL REPRESENTATIONS

\( 45_H, \ 16_H \) (and \( 16_H \) in SUSY)

\[ \downarrow \]

non-renormalizable interactions

\[ \downarrow \]

similar to \( SU(5) \),

uncertainties in both \( d = 6 \)

and \( d = 5 \)
(ii) LARGE REPRESENTATIONS

\[ 210_H, \overline{126}_u \ (\text{and} \ 126_H \ \text{in} \ 5u \gamma) \]

but possible at the renormalizable level

\[ \langle \overline{126}_u \rangle \quad \langle 1,3,10 \rangle \quad \text{mass to} \ \nu_R \]

\[ \langle (2,2,15) \rangle \quad \text{charged fermion masses} \]

\[ \downarrow \]

correct mass spectrum

Raby, Hocheptitl '92

MORE: type II see-saw

Large \( \Theta_{\text{atm}} \) \( \Leftrightarrow \) b-\( \tau \) unification

Bajc, Visani, G.S.

\[ \theta_0 \text{ or } \theta_1, \ \text{large} \ \theta_{13} = 15^\circ \]

Gol, Hocheptitl, Ny
UNIFICATION CONSTRAINTS
and p-decay in SOC(10)

• NO SUPERSYMMETRY (OR LARGE SCALE)

INTERMEDIATE MR, MPS  BUT

Mx NOT PREDICTED

CAN LOWER Mx ⇒

POSSIBLE \( T_p (d=6) \approx 10^{33} \) yr

GENERICALLY: \( T_p > 10^{33} \) yr

• LOW ENERGY SUPERSYMMETRY ⇒

USUAL STORY OF \( d=5 \)

(STILL UNCERTAIN)
• SPLIT SUSY

oscillates between susy and no-susy, depend on $m_f$

↓ ALL THIS!

needs badly a new generation of p decay experiments

• COMMENT

SPLIT SUSY: DARK MATTER UNIFICATION

NO SUSY:

UNIF. OK IN SO(10)

DARK MATTER CAN BE AXIONS

($\mathbb{PQ}$ NATURAL IN $SO(10)$: $16 \to e^{i\theta} 16$)
SUMMARY

- $p$ decay rate not predicted precisely, not even in minimal SUSY $SU(5)$ uncertainties in $M_X, M_T$

- Minimal (realistic) SUSY $SU(5)$ still OK, but $d=5$ $p$ decay close to $10^{33}$ dangerously

- Non-SUSY end split SUSY: $p$ decay naturally $10^{33} - 10^{36}$ yr
  (could be larger, but needs tuning of parameters)

- Grand unification cries for a new generation of $p$ decay experiments