Dimension-Five Operators in Grand Unified Theories

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Unification and Proton Decay

GUTs provide an appealing extended framework for understanding the standard model.

- Coupling constants in MSSM unify at $M_{GUT} \sim 2 \times 10^{16}$ GeV.
- Fermions in a generation can be unified in one or two simple reps.
- Hyper/electric-charge quantized.
- Anomaly cancellation can be automatic.
- Seesaw mechanism generates small but non-zero masses for neutrinos.

Hierarchy Problem: Large difference between weak and GUT scales problematic due to quadratic Higgs corrections.

$\longrightarrow$ Supersymmetry: Stabilizes hierarchy problem.

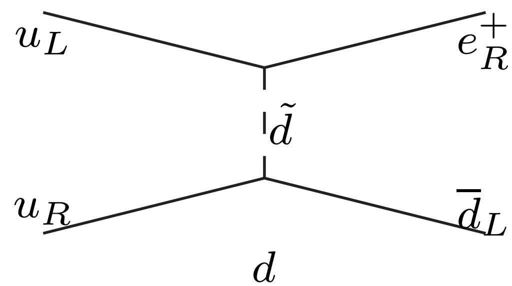
But, proton decay is enhanced via supersymmetric operators.

Proton Decay in Supersymmetric Theories

MSSM allows dimension-four operators which violate baryon or lepton number:

$$QLd^c, \quad u^c d^c d^c, \quad LLe^c$$

These mediate rapid proton decay, e.g.



Relevant proton decay operator is suppressed only by sfermion mass squared.
$\rightarrow$ These operators must be highly suppressed or forbidden.
Impose matter parity:

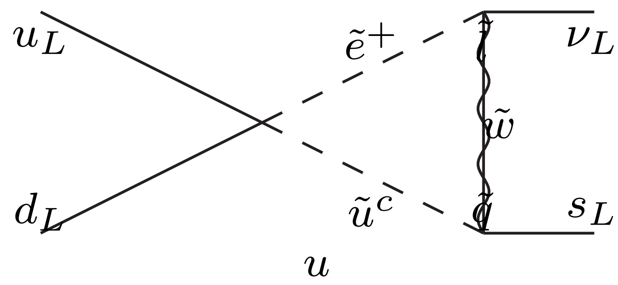
- Z_2 symmetry.
- Higgs and gauge superfields: +1.
- Matter superfields: -1.
- Subgroup of $U(1)_{B-L}$.
- Equivalent to R-parity.

Dimension-five Operators

Matter parity allows dimension-five operators:

$$QQQL, \quad u^c d^c u^c e^c$$

Generated by integrating out color-triplet Higgs in a GUT.



$\longrightarrow$ Higgs triplets must be at GUT scale. (Doublet-Triplet splitting).

Planck-scale Operators

Regardless of unification these operators can arise via gravity .
$\rightarrow$ Naively suppressed by one power of the Planck mass, $M_P \simeq 2 \times 10^{18}$ GeV.

$\rightarrow$ Coeffecients $\leq 10^{-7}$.

Possibly appeal to smallness of Yukawa couplings generated by flavor symmetry. However,

- Global symmetries may not be exact in nature.
- Gauge symmetries difficult to imbed in GUTs.
- Symmetries which generate adequate Yukawas don't necessarily provide sufficient suppression.

Question

To What Extent Can We Suppress Dangerous Planck-Scale Operators By The Choice of Gauge Group?

Consider promising GUT groups

$SO(10), \quad E_6, \quad G_{TR} \equiv SU(3)_C \times SU(3)_L \times SU(3)_R \times Z_3.$

- $U(1)_{B-L}$ subgroups allow R-parity.
- Provide right-handed neutrino needed for seesaw mechanism.
- All fermions in a generation in a single representation.
- $SO(10)$ and G_{TR} can be considered as GUTs in themselves or as subgroups of E_6.

SO(10)

- SM fermions in spinor $\mathbf{16}_M$ representation.
- MSSM Higgs in vector $\mathbf{10}_H$.
- Dimension-four operator $(\mathbf{16}_M)^3$ forbidden.

If $U(1)_{B-L}$ broken by Higgs of even congruency class, e.g. $\overline{\mathbf{126}}_H$, then matter parity is preserved as a discrete gauge symmetry.

If broken by odd congruency Higgs, e.g. $\mathbf{16}_H$, Higgs and Matter fields are not distinct. Must impose extra symmetry to produce matter parity.

$$\frac{1}{M_P}(\mathbf{16}_M)^3\mathbf{16}_H \supset \frac{1}{M_P}\overline{\mathbf{5}}_M\overline{\mathbf{5}}_M\mathbf{10}_M N_H \rightarrow \frac{\langle N_H\rangle}{M_P}\overline{\mathbf{5}}_M\overline{\mathbf{5}}_M\mathbf{10}_M \supset QLd^c + u^c d^c d^c + LLe^c$$

Dim-4 operators suppressed by $\frac{M_{GUT}}{M_P} \sim 10^{-2}$.

Dim-5 operators allowed at GUT scale: $(\mathbf{16}_M)^4 \supset QQQL + u^c d^c u^c e^c$.

Flavor symmetries must suppress these operators at 10^{-7} level.

E_6

Consider $E_6 \supset SO(10) \times U(1)$.

- Matter in $\mathbf{27} \rightarrow \mathbf{16}_1 + \mathbf{10}_{-2} + \mathbf{1}_4(S)$.
- Fermion masses generated by $\overline{\mathbf{27}} \times \overline{\mathbf{27}} = \mathbf{27} + \mathbf{351} + \mathbf{351}'$.
- Dim-4 operator allowed by gauge symmetry: $(\mathbf{27})^3$.

Nonetheless R-parity may be preserved depending on the Higgs used to break E_6.

Analogous to $SO(10)$, R-parity broken if $\mathbf{16}_1 \subset \mathbf{27}$ acquires a vev, preserved if $\overline{\mathbf{126}}_{-2} \subset \mathbf{351}'$ used.

Dimension-five operators $(\mathbf{27}_M)^4$ forbidden by GUT symmetry.

Dimension-five Operators and Extra Matter

Dim-5 operators can be generated from higher dimension operators once E_6 is broken.
e.g.
$\frac{1}{M_P}(\mathbf{27}_M)^4\overline{\mathbf{27}}_H \supset \frac{1}{M_P}(\mathbf{16}_M)^4\overline{S}_H \to (\mathbf{16}_M)^4\frac{M_{GUT}}{M_P}$.

Also note $\mathbf{27}_{\mathrm{M}}\mathbf{27}_{\mathrm{M}}\mathbf{27}_H \supset \mathbf{16}_M\mathbf{16}_M\mathbf{10}_H + \mathbf{16}_M\mathbf{10}_M\mathbf{16}_H + \mathbf{10}_M\mathbf{10}_M S_H$.

So a vev for S_H generates both dim-5 operators and masses for extra matter.
This is true because under $SO(10)\times U(1)$ both $(\mathbf{10}_{-2})^2$ and $(\mathbf{16}_1)^4$ contain $\mathbf{1}_{\pm 4}$.

Equally true if we used $\mathbf{45}_4 \subset \mathbf{351}$ or $\mathbf{54}_4 \subset \mathbf{351}'$.

It can be shown generally that *any Higgs field which gives mass to the extra matter in a 27 also generates dimension-five proton decay operators, regardless of the breaking scheme between E_6 and the SM*.

Intermediate Scales

To sufficiently suppress proton decay, introduce an intermediate scale vev to generate masses for the $\mathbf{10}_M$.

$$\frac{M_I}{M_P} \leq 10^{-7} \tag{1}$$

Since $\mathbf{10}_M$ is composed of complete $SU(5)$ multiplets coupling unification is not spoiled.

An example:
Consider two Higgs fields in the $\mathbf{351}'$ rep and one in the adjoint $\mathbf{78}$.

$$E_6 \quad \xrightarrow[\mathbf{351}'_{H1}]{} SO(10) \quad \xrightarrow[\mathbf{351}'_{H2}]{} SU(5) \quad \xrightarrow[\mathbf{78}_H]{} SM \tag{2}$$

R-parity is preserved, this was *not* required.

Thus far *no* dangerous dim-5 operators, *but* $\mathbf{10}_M$ remains massless. Due to a remnant discrete symmetry.

$\rightarrow$ include a $\mathbf{27}_H, \mathbf{351}_H$, or $\mathbf{351}'_H$ which acquires an intermediate vev.

Consequences of an Intermediate Scale

An appropriate M_I can suppress dangerous proton decay operators and leave the exotic matter heavy enough to satisfy precision electroweak bounds.

Inclusion of 3 generations of $\mathbf{10}_M$, $M_I \sim 10^{10}$ GeV.

- Good unification retained.
- $M_{GUT} \rightarrow 1.6 M_{GUT(MSSM)}$.
- Unification remains perturbative.
- $\mathbf{10}_M$ matter mixes with down quarks and leptons at order $\frac{M_W}{M_I}$.

Superpotential remains to be constructed.
Note however $M_I^2/M_{GUT} \sim M_W \rightarrow$ hierarchy problem not exacerbated.

Trinification

An equivalent scheme can be implemented in $G_{TR} \equiv SU(3)_C \times SU(3)_L \times SU(3)_R \times Z_3$.

- Maximal subgroup of E_6.
- $\mathbf{27}_M \supset (1,3,\overline{3}) + (\overline{3},1,3) + (3,\overline{3},1) \equiv \mathsf{L} + \mathsf{Q}^c + \mathsf{Q}$.
- Extra matter $B; B^c$; and E, E^c, S in Q; $\mathsf{Q}^c$and L respectively.

Minimal model:

$$G_{TR} \quad \xrightarrow[S_H]{} SU(3) \times SU(2) \times SU(2) \times U(1) \quad \xrightarrow[N_H \subset \mathbf{16}]{} SU(3) \times SU(2) \times U(1).$$

- R-parity broken, must impose additional matter parity.
- Dim-5 operators generated from dim-6, e.g. $\mathsf{Q}_M \mathsf{Q}_M \mathsf{Q}_M \mathsf{L}_M \overline{\mathsf{L}}_H$.

Alternative:

$$G_{TR} \quad \xrightarrow[(1,\overline{6},6)]{} SU(3) \times SU(2) \times SU(2) \times U(1) \quad \xrightarrow[(1,\overline{6},6)]{} SU(3) \times SU(2) \times U(1).$$

+ R-parity automatic.
+ Dim-5 operators have not appeared.

  Exotic matter massless until an intermediate scale which generates suppressed dim-5 operators.

Conclusions

- Proton decay is a generic problem for supersymmetric theories.
- In addition to standard dim-4 and dim-5 operators generated at GUT scale, we should be concerned about these operators generated at the Planck scale.
- In absence of family symmetries typically suppressed by only $\frac{M_{GUT}}{M_P} \sim 10^{-2}$ if at all.
- E_6 derived theories offer possibility of forbidding dim-4 and sufficiently suppressing dim-5 in context of a unified gauge theory.
- Dim-5 operators will be induced at some scale in order to give mass to exotic matter. This is true *regardless* of the breaking scheme.
- Therefore introduce an intermediate scale $M_I \leq 10^{-7} M_P$, possibly related to weak scale.