Proton Decay in SUSY GUTs revisited

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Contents of my talk

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This talk is based on recent works,
   JH, Kobayashi, Muramatsu, and Nagata, arXiv:1302.2194
   JH, Kuwahara, and Nagata, arXiv:1304.0343
1. Introduction

Grand Unified Theories (GUTs)

- Unification of gauge groups
  \[ SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(5), \ SO(10), \ E_6 \]
- Unification of quarks and leptons

In \( SU(5) \) GUTs

\[
\psi(10) = (u_L, d_L, (u_R)^c, (e_R)^c) \\
\phi(5^*) = ((d_R)^c, \nu_L, e_L)
\]

Electric charge quantization is automatic.

\[
|Q_p + Q_e| < 10^{-21}
\]

Prediction of GUTs:

- Gauge coupling unification
- Proton decay
Gauge coupling unification

- Supersymmetry (SUSY), which is a symmetry between boson and fermion, is needed for the gauge hierarchy problem. The standard model (SM) should be supersymmetric around TeV scale in the GUTs.

- If the minimal supersymmetric standard model (MSSM) is realized at TeV scale, the three SM gauge coupling coupling constants meets at $2 \times 10^{16}$ GeV.

Grand Desert from MSSM to SUSY GUTs has been considered the most promising paradigm for beyond SM after LEP I experiments.
X boson proton decay in SUSY SU(5) GUTs

X bosons are SU(5) partners of SM gauge bosons. Main decay mode is $p \rightarrow e^+ \pi^0$.

Effective baryon-number violating operators are dim=6.

When MSSM at TeV scale is assumed,

$$\tau_p \simeq 1.2 \times 10^{35} \text{years} \times \left( \frac{M_X}{10^{16}\text{GeV}} \right)^4$$

From experimental bound, $\tau_{p \rightarrow e^+ \pi^0} > 1.29 \times 10^{34} \text{years}$

$$M_X > 0.6 \times 10^{16}\text{GeV}$$

SuperKamiokande experiment is approaching close to the GUT scale.
Colored Higgs proton decay in SUSY SU(5) GUTs

Colored Higgses are SU(5) partners of SU(2) doblet Higgses in MSSM. Colored Higgs exchange induces dim=5 baryon-number violating operators, which include squarks or sleptons, and they become dim=6 operators with SUSY particle exchange.

\[
\begin{align*}
&q \\ &\tilde{H}_C \\ &\tilde{W}, \tilde{H} \\ &\tilde{l} \\ &q
\end{align*}
\]

Main decay mode is \( p \rightarrow K^+ \bar{\nu} \).

Assuming Higgsino exchange dominates over gaugino ones,

\[
\tau_p \approx 2 \times 10^{31} \text{years} \times \sin^4 2\beta \left( \frac{M_{HC}}{10^{16} \text{GeV}} \right)^2 \left( \frac{M_{SUSY}}{\text{TeV}} \right)^2
\]

while experimental bound is \( \tau_{p\rightarrow K^+\nu} > 3.3 \times 10^{33} \text{years} \).

Various models are constructed to suppress the proton decay.
“The discovery of the Higgs with a mass of 125 GeV makes proponents of the MSSM nervous.”
(from MSSM Higgs mass in Wikipedia)

Higgs mass bound in MSSM

\[ m_h^2 \leq m_Z^2 \cos^2 2\beta + \frac{3}{\pi^2} \frac{m_t^4 \sin^4 \beta}{v^2} \left( \log \frac{m_{\tilde{t}}}{m_t} + a^2 \left(1 - \frac{a^2}{12}\right) \right) \]

Proposals to push up Higgs mass:

- TeV scale SUSY with large A term
- NMSSM
- Extra gauge interactions
- Extra matters coupled with Higgs boson
- High scale SUSY (sfermion masses are \(10^{2-3}\) TeV scale)
- etc...
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My personal opinion;
If the Higgs boson is elementary, SUSY is still interesting.
If SUSY exits, theories may involve the Grand Desert.
In fact, the gauge coupling unification is still beautiful.
“The discovery of the Higgs with a mass of 125 GeV makes proponents of the MSSM nervous.” (from MSSM Higgs mass in Wikipedia)

Proposals to push up Higgs mass:

• TeV scale SUSY with large A term
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Proposals to push up Higgs mass:

- TeV scale SUSY with large A term
- NMSSM
- Extra gauge interactions
- **Extra matters**
- High scale SUSY (sfermion masses are $10^{2-3}$ TeV scale)
- etc...

Some hints for SUSY GUTs may be hidden in these ideas.
2, Extra matters

Additional extra maters to MSSM are sometimes proposed.

- Radiative correction to Higgs mass.
- Gauge mediation
- 5 and 5* in $E_6$ GUTs and extra family in string theories.

Introduction of SU(5) complete multiplets does not disturb the gauge coupling unification.
Extra matters

Additional extra matters to MSSM are sometimes proposed.

- Radiative correction to Higgs mass.
- Gauge mediation
- 5 and 5* in E₆ GUTs

Introduction of SU(5) multiplets do not disturb the gauge coupling unification.

Introduction of extra matters enhances X-boson proton decay rate since the gauge coupling constant becomes stronger at the GUT scale.
Proton decay in SUSY SU(5) GUTs with extra matter in intermediate scale

Introduction of extra matters enhances proton decay rate due to larger gauge coupling constants at GUT scale.

Suppression factors for proton lifetime, compared with the case without extra matters, as functions of mass for extra matters.

Light gray and gray regions for $M_X = 1 \times 10^{16}, 2 \times 10^{16}$ GeV, respectively are excluded.
Radiative corrections to proton decay rates

Larger coupling could enhance the proton decay rate by the radiative correction.

The renormalization group equations for Wilson coefficients for the D=6 operators are evaluated at one-loop level.
Radiative corrections to proton decay rates

We derive the renormalization group equations for Wilson coefficients for the D=6 operators at two-loop level.

We found that two-loop correction to the event rate quite small.

This comes from accidental cancellation between two-loop corrections to gauge coupling and Wilson coefficients, while the corrections could change the rate larger than $O(10)\%$.

(JH, Kobayashi, Muramatsu, Nagata (12))

Threshold correction at GUT scale is now being evaluated at one loop level.
Tips

Effective operator in Khaeler potential (without covariant derivative)

\[ K_\mathcal{O} = \Phi_A^\dagger (\phi_1^\dagger, \phi_2^\dagger, \cdots) [e^V]_{AB} \Phi_B (\phi_1, \phi_2, \cdots) \]

Anomalous dimension for the operator is easily derived without evaluation of diagrams, if you use effective Khaeler potential for general Khaeler potential, with \[ K = \sum_i \phi_i^\dagger e^V \phi_i \rightarrow \sum_i \phi_i^\dagger e^V \phi_i + K_\mathcal{O} . \]

Anomalous dimension at one-loop level is derived as

\[ \gamma_\mathcal{O}^{(1)} = \sum_\alpha \frac{g_\alpha^2}{16\pi^2} \left( 4C_\mathcal{O}^\alpha - 2 \sum_i C_\alpha(i) \right) \]

where \( C^\mathcal{O} \) is Casimir for \( \Phi_A \) (or \( \Phi_B \)) and \( C(i) \) are for fields in the operator. Now only gauge int. is considered.

Two-loop level effective Khaeler potential is derived by Nibbelink, Groot and Nyawelo. We used it for two-loop anomalous dim.
3, High-scale SUSY

High-scale SUSY, in which scalar bosons except for the SM Higgs have mass around $10^{2-3}$ TeV, is a possible solution for the Higgs mass.

- Squarks and slepton masses are comparable to gravitino mass.
- Gaugino masses are one-loop suppressed compared with gravitino masses (anomaly mediation).
- Higgsino mass could be order of gravitino mass, though accidental symmetries suppress it.
- LSP is Wino or Higgsino. The thermal relics for wino and Higgsino are good for mass 3 or 1 TeV, respectively.
GUT-scale mass spectrum

In the minimal SUSY SU(5) GUT, superheavy states are X boson, colored Higgses, and SU(5) breaking adjoint Higgs. The mass spectrum can be constrained from the gauge coupling unification, since differences among the gauge coupling const. at weak scale come from the mass differences among components in SU(5) multiplets.

• Colored Higgs and SU(2) doublet Higgs mass difference

\[
\frac{3}{\alpha_2(m_Z)} - \frac{2}{\alpha_3(m_Z)} - \frac{1}{\alpha_1(m_Z)} = \frac{1}{2\pi} \left[ \frac{12}{5} \ln \left( \frac{M_{HC}}{m_Z} \right) - 2 \ln \left( \frac{M_S}{m_Z} \right) + 4 \ln \left( \frac{M_3}{M_2} \right) \right]
\]

\( M_S \) : Masses for Higgsino and Heavy Higgs boson in MSSM

\( M_3, M_2 \) : Masses for gluino and wino.

• Mass difference in gauge sector

\[
\frac{5}{\alpha_1(m_Z)} - \frac{3}{\alpha_2(m_Z)} - \frac{2}{\alpha_3(m_Z)} = \frac{1}{2\pi} \left[ 12 \ln \left( \frac{M_X^2 M_\Sigma}{m_Z^3} \right) + 4 \ln \left( \frac{M_2}{m_Z} \right) + 4 \ln \left( \frac{M_3}{m_Z} \right) \right]
\]

\( M_X, M_\Sigma \) : X boson and adjoint Higgs masses, respectively.

(JH, Kuwahara, Nagata (13))
GUT-scale mass spectrum

- Squarks and sleptons are assumed to have masses equal to Higgsino and heavy Higgs bosons in MSSM, $M_S$.
- In pure anomaly mediation $M_3/M_2 \sim 11$, while the ratio may be corrected by Higgs-Higgsino loops.

Low-energy SUSY predicts colored Higgs mass around $10^{15}$ GeV (blue bands in figs), while the gauge coupling unification can be improved in high-scale SUSY.
The GUT scale \( M_{\text{GUT}} \equiv (M_X^2 M_\Sigma)^{1/3} \) is slightly lowered when the gauginos are heavier. X boson proton decay may be accessible. When \( M_X = M_{\text{GUT}} \), \( \tau_p \propto (M_{\text{gaugino}})^{-8/9} \).
Colored Higgs proton decay

Colored Higgs exchange two types of dim=5 baryon-number violating operators; one is composed of left-handed quarks and leptons and another is of right-handed ones.

The proton decay diagrams include wino or Higgsino exchange, and amplitudes are proportional to wino or Higgsino mass.
Colored Higgs proton decay

\[ M_{H_C} = 10^{16} \text{ GeV} \]

Higgsino mass is equal to squark/slepton mass. Wino mass is 3 TeV.

Colored Higgs proton decay escapes from experimental bound, and the minimal SUSY SU(5) GUT is still viable without introducing any mechanism. In addition, Future experiments may be accessible, depending on parameters.
Colored Higgs proton decay

\[ M_{HC} = 10^{16} \text{ GeV} \]

Squark/slepton masses are 10^3 TeV.
Wino mass is 3 TeV.

The Higgsino exchange dominates over the wino exchange.
Summary

In my talk, I discuss proton decay in SUSY SU(5) GUTs. My personal opinion is that the gauge coupling unification is still beautiful. If the Higgs boson is elementary, SUSY, which may involve the Grand Desert, is still interesting. I consider two cases.

• Introduction extra matter at intermediate scale
• High-scale SUSY

In both cases, the proton decay may be enhanced compared with traditional MSSM. Future proton decay searches may give important information for SUSY and GUTs.