Proton Decay and GUTs

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Why do we pursue proton decay?

- Minimal SU(5) GUT excluded by IMB
- Minimal SUSY SU(5) GUT excluded by SuperKamiokande
- Why do we still look for proton decay?
- I will argue:
  - Many reasons to believe proton should decay
  - Can probe Planck-scale if supersymmetry
Outline

• Why We Expect Proton Decay
• Data
• GUTs
• Supersymmetry w/o GUT
• Conclusions
Why We Expect Proton Decay
Problem with Anti-Matter

• Anderson discovered positron $e^+$, anti-matter of electron in 1932
• A very naïve question:
  Why doesn’t proton decay $p \rightarrow e^+ \gamma$ ?
• Stückelberg (1939) made up a new conservation law:
  Baryon number must be conserved
(later also by Wigner, 1949)
Lepton Family Number

- Similarly ad-hoc conservation law
- Neddermeyer-Anderson discovered muon in 1937
- A very naïve question: Why doesn’t muon decay $\mu^- \rightarrow e^- \gamma$?
- Inoue-Sakata made up a new conservation law: Lepton Family number must be conserved
- Neutrino oscillations (SuperK, SNO, KamLAND) have disproven lepton family number conservation!
Sacred and secular laws

- **Sacred conservation laws**: consequences of fundamental principles such as gauge invariance, Lorentz invariance, unitarity
  - *e.g.*, electric charge, CPT, energy-momentum
- **Secular conservation laws**: Happen to be approximately true, but ultimately violated
  - *e.g.*, parity, CP, lepton family
Fate of Secular Conservation Laws

- Parity: Fallen 1956
- Charge Conjugation: Fallen 1956
- CP: Fallen 1964
- T: Fallen 1999
- Lepton Family: Fallen 1998 (µ), 2002 (e)
- Lepton Number: Still viable (0νββ?)
- Baryon Number: Still viable
Baryon Number is Probably Violated

- Universe is made of baryons, no anti-baryons
  - There must have been a process in early Universe that created this asymmetry via baryon number violation
  - Such baryon number violation may (but not necessarily) lead to proton decay
- Old philosophy (e.g., Yang-Mills): all conserved quantities must be local gauge charges
- Quantum gravity (virtual blackholes, wormholes) violate global (non-gauge) charges
- Standard Model itself violates $B$ by anomalies: $\Delta B = \Delta L = 3$
  \[ \tau(t \rightarrow e^+ \nu_\mu \nu_\tau) \sim 10^{150} \text{ years} \]
Baryon Number as an Accidental Symmetry

- In the Standard Model, the proton is absolutely stable
- $B$ is an “accidental” symmetry, *i.e.*, there is no renormalizable interaction you can write down that violates $B$ with the minimal particle content
- But once beyond the Standard Model, there is no reason for $B$ to be conserved.
- Grand Unified Theories prime example of well-motivated theories that lead to proton decay
- But doesn’t have to be GUTs
Data
Super-KamiokaNDE
Nucleon Decay Experiment

- Kamioka Mine in central Japan
- ~1000m underground
- 50kt water
- Inner Detector
  - 11,200 PMTs
- Outer Detector
  - 2,000 PMTs
GUTs
Proton Decay in GUTs

- Quarks and leptons in the same multiplet
- Gauge bosons can convert $q$ to $l$
- Cause proton decay! $p \rightarrow e^+ \pi^0$
- IMB excluded the original SU(5)
- Minimal SUSY GUT:
  $\tau(p \rightarrow e^+ \pi^0) = 31 \times 10^{34}$ yr $(M_X/1.4 \times 10^{16}$ GeV)$^4$
- SuperK: (90% CL)
  $\tau(p \rightarrow e^+ \pi^0) > 0.57 \times 10^{34}$ yr
Supersymmetric Proton Decay

\[ \Gamma \propto \left( \frac{g^2}{(4\pi)^2} \frac{h_sh_c \theta_C^2}{M_{HC} m_{SUSY}} \right)^2 m_p^5 \]

Suppressed only by the second power of GUT scale vs fourth in X-boson exchange

Exchange of fermionic superpartner of color-triplet SU(5) partner of Higgs boson
Rest In Peace

Minimal SUSY SU(5) GUT

Gauge coupling unification:

- SuperK limit $\tau(p \rightarrow K^+\nu) > 2.3 \times 10^{33}$ years (90% CL)
  $M_{H_c} > 14 \times 10^{16}$ GeV
- Even if 1st, 2nd generation scalars “decoupled”, 3rd generation contribution
  (Goto, Nihei)
  $M_{H_c} > 11 \times 10^{16}$ GeV
  (HM, Pierce, updated)
Fine-tuning

• Requires bad fine-tunings to salvage this model
  – Add extra Planck-suppressed operators that modify Yukawa couplings (Emmanuel-Costa, Wiesenfeldt)
  – Fiddle with flavor structure of scalar masses-squared matrices (Bajc, Perez, Senjanovic)
  – Raise the SUSY masses giving up the hierarchy problem (Arkani-Hamed, Dimopoulos)
It doesn’t rule out
SUSY-GUT in general

• Unfortunately, the prediction of the proton decay via $D=5$ operator is sensitive to the ugliest aspect of the SUSY-GUTs
  – Triplet-doublet splitting
  – Fermion mass relation $m_l=m_d$

• Any “solution” to these big problems is likely to modify the proton decay prediction.
Triplet-Doublet Splitting

Orbifold GUT Breaking

- Break SU(5) by boundary conditions on extra line segment $S^1/Z_2$
- Natural triplet-doublet splitting
- No $D=5$ operator
- Compactification scale $M_c \sim 10^{15}$ GeV
- Can have new $D=6$ operators on the fixed point $\sim 1/M_c^2$
  (Kawamura; Hall, Nomura)
Supersymmetry w/o GUT
Supersymmetry

- Supersymmetry predicts new particles
- Gauge invariance allows baryon- and lepton-number violating interactions even within the MSSM
- **Baryon number violation**: \( W = u dd \)
- **Lepton number violation**: \( W = Q d L + L L e + L H_u \)
- **Baryon number is no longer conserved**
  “accidentally”
- If both types present, they will induce proton decay
**R-parity**

- If GUT, $udd \& QdL$ both in $10^5 \times \tilde{5}^* 

- If they exist with $O(1)$ couplings:
  \[ \tau_p \sim m_{sq}^4 / m_p^5 \sim 10^{-12} \text{ sec!} \]

- Product of two couplings $< 10^{-26}$

- Impose $R$-parity $= (-1)^{3B+L+2S}$

- Forbids baryon and lepton number violation
  \[ W = udd + QdL + LLe + Lh_u \]

- $R$-parity is non-anomalous; may be gauged

- **Stable Lightest Supersymmetric Particle**  
  $\Rightarrow$ **Cold Dark Matter**
Dirty Little Secret about Supersymmetry

• But $R$-parity is not enough!
• Once supersymmetry is there, with or without grand unification, *Planck-scale physics can cause too-rapid proton decay*
• Dangerous operators:

\[
\frac{h}{M_{Pl}} Q_1 Q_1 Q_2 L_i \quad \frac{h}{M_{Pl}} Q_1 Q_2 Q_2 L_i
\]

• Typically, $h < 4 \times 10^{-8}, 10^{-7}$, respectively
  (Kakizaki, Yamaguchi)
But there are small numbers

• But remember that we actually do see small numbers in our daily life.
But there are small numbers

• But remember that we actually do see small numbers in our daily life.

• Yukawa couplings for 1st, 2nd generations are pretty small. Using $\lambda \sim \theta_c \sim 0.22$, $h_u/h_t \sim \lambda^8$, $h_d/h_b \sim \lambda^4$, $h_e/h_t \sim \lambda^5$

• Aren’t they unnatural?

  Yes, of course!
### Broken Flavor Symmetry

- **Flavor quantum numbers (SU(5)-like):**
  - $10(Q, u_R, e_R)$ (+4, +2, 0)
  - $5^*(L, d_R)$ (+2, +2, +2)

- **Flavor symmetry broken by a VEV $\langle \lambda \rangle \sim 0.22$**

| \(M_u\) \~ \(\begin{pmatrix} \lambda^8 & \lambda^6 & \lambda^4 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 1 \end{pmatrix}\) | \(M_d\) \~ \(\begin{pmatrix} \lambda^6 & \lambda^6 & \lambda^6 \\ \lambda^4 & \lambda^4 & \lambda^4 \\ \lambda^2 & \lambda^2 & \lambda^2 \end{pmatrix}\) | \(M_l\) \~ \(\begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^6 & \lambda^4 & \lambda^2 \end{pmatrix}\) |

- \(m_u : m_c : m_t \sim m_d^2 : m_s^2 : m_b^2 \sim m_e^2 : m_\mu^2 : m_\tau^2 \sim \lambda^8 : \lambda^4 : 1\)
- **Neutrinos are anarchy** (Hall, HM, Weiner; Haba, HM; de Gouvêa, HM)
Flavor Symmetry Suppresses Proton Decay, too!

- Once the quarks and leptons carry a new charge, it would forbid the dangerous proton decay operators.
- Proton decay may be suppressed because of the same reason why 1st and 2nd generation particles are light. (HM, D.B. Kaplan)
  \[ \frac{h}{M_{Pl}} Q_1 Q_1 Q_2 L_i \quad \frac{h}{M_{Pl}} Q_1 Q_2 Q_2 L_i \]
- Previous charge assignment gives \( h \sim \lambda^{12} \sim 1.4 \times 10^{-8} \) - *Interesting number!*

Does this happen in a concrete model?

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A Very Ambitious Model

• Use string-inspired anomalous U(1) for everything
  – The only symmetry beyond $SU(3)_C \times SU(2)_L \times U(1)_Y$
  – Only two right-handed neutrinos
  – No new mass scales except for $M_{Pl}$ and $m_{SUSY}$
  – Quark masses and CKM matrix
  – Lepton masses
  – Right-handed neutrino masses (no GUT-scale)
  – Left-handed neutrino masses and MNS matrix
  – $R$-parity as an unbroken subgroup of $U(1)$
  – Adequate suppression of proton decay?
    (Dreiner, HM, Thormeier)
$\tau(p \rightarrow K^+\bar{\nu})$ yrs

$p\rightarrow K^+\bar{\nu}$, incoherent

limit

destructive

constructive

$\beta = 0.01$ GeV$^3$, $m_{\text{soft}} = 1$ TeV

$x = 0$, $x = 1$, $x = 2$, $x = 3$

$z = 0$ (Anarchy), $z = 1$ (Semi-Anarchy)

Models

Harnik, Larson, HM, Thormeier
Conclusions

• *Supersymmetry connects proton decay to GUT- and even Planck-scale physics*

• Baryon Number Violation is naturally expected at some level with or without grand unification

• Proton decay suppression may well be due to the same reason why electron is light

• Models suggest rates at “interesting” levels