No GUTs Needed: Planck Scale Nucleon Decay

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Unification Day Workshop
Keystone, CO – October 15, 2004

Based on hep-ph/0404260 with
R. Harnik, H. Murayama, and M. Thormeier
Motivation

- Baryon Number is an accidental symmetry of the Standard Model
  - No renormalizable $B$-violating operators are allowed
    by the gauge symmetries and SM particle content.

- New particles have the potential to violate Baryon Number

- A well known example:
  - GUT theories have new Gauge and Higgs bosons
    that destabilize the proton.
Two Simple Questions
Question 1

Question 1: Does observation of proton decay imply a Grand Unified Theory?
**Question 1**

- **Question 1:** Does observation of proton decay imply a Grand Unified Theory?

  - No! Supersymmetric theories also have new particles with many Baryon and Lepton number violating interactions.

  ![Diagram](image)

  \[ P \rightarrow \pi^+ \rightarrow e^- \]

  \[ \text{GUT} \]

  \[ \text{LLE} \quad \text{QDL} \quad \mu'\text{LH} \quad \text{UUDE} \]

  \[ \text{QQQL} \quad \text{UDD} \]
Question 2: Does $R$-parity protect the proton?
Question 2

- **Question 2:** Does $R$-parity protect the proton?

  - No! Renormalizable $B$ and $L$ violating operators are prohibited, but dimension 5 proton decay is still allowed.
  - Even when Planck suppressed: $\tau_p \sim 10^{17}$ years!
  - Small coefficients are required.
  - SUSY’s “Dirty Little Secret”
Proton Decay Operators
Standard Model

- **Standard Model GUT**

  - Proton decay mediated by $X$ gauge bosons at $M_{\text{GUT}} \sim 10^{15}$ GeV

  \[
  \Gamma_{\text{SM}} \sim \frac{\alpha_{\text{GUT}}^2}{M_{\text{GUT}}^4} m_p^5 \Rightarrow \tau_{p}^{\text{SM}} \sim \frac{M_{\text{GUT}}^4}{m_p^5} \sim 10^{31} \text{ years}
  \]

  - Experimentally ruled out

  - Also, SM couplings **DO NOT** unify.
Supersymmetric GUTs

- Couplings DO unify
- ... and at a higher scale: $M_{\text{GUT}} \sim 10^{16}$ GeV

$$\Gamma_{\text{SUSY}} \sim \frac{\alpha^2_{\text{GUT}}}{M_{\text{GUT}}^4} m_p^5 \quad \Rightarrow \quad \tau_p^{\text{SUSY}} \sim \frac{M_{\text{GUT}}^4}{m_p^5} \sim 10^{35} \text{ years}$$

- Such a lifetime is not yet probed experimentally.
- But these are dimension-6 operators...
Minimal $SU(5)$ SUSY-GUT

- Colored Higgs exchange generates dimension-5 operators.
Minimal $SU(5)$ SUSY-GUT

- They are “dressed” by gaugino and higgsino exchange to form 4-fermion operators.

- Thus $\tau_p \sim \frac{1}{M_{GUT}} \frac{M_{\text{gaugino}}}{M_{\text{squark}}}^2$ instead of $\frac{1}{M_{GUT}} \frac{1}{M_{\text{soft}}}$. 
  - But the coefficients come from small Yukawa couplings.
  - Minimal $SU(5)$ SUSY-GUT excluded experimentally

[Murayama and Pierce, hep-ph/0108104]
SUSY without GUTs

- Effective Theory: **dim-5** operators generated by Planck scale physics

\[ \tau_p \sim \frac{1}{C^2} \frac{M_{\text{Planck}}^2 M_{\text{soft}}^2}{m_p^5} \].

- Lifetime is too short with \( \mathcal{O}(1) \) coefficients: \( \tau_p \sim 10^{17} \) years!
- A symmetry that explains the small \( LEH \) coefficient (electron mass) should also yield \( QQQL \) coefficients.
Flavor Model Framework
$U(1)_X$ for Everything

[Dreiner, Murayama, Thormeier: hep-ph/0312012]

- The MSSM with minimal additions:
  - One additional gauge symmetry, an anomalous $U(1)_X$ (flavor)
  - One additional flavon $A$
  - Two right-handed neutrinos
  - Only two mass scales: $M_{Pl}$ and $M_{soft}$
$U(1)_X$ for Everything

- **String theory motivation**
  - Green-Schwarz mechanism cancels $U(1)_X$ anomalies
    
    $S \to S - i\delta_{GS} \Lambda_X$

    [Green, Schwarz, PLB (1984)]

  - Generates a Fayet-Iliopoulos $D$-term for $U(1)_X$

    [Dine, Seiberg, Wen, Witten, NPB (1986, 1987)]

    [Atick, Dixon, Sen, NPB (1987); Dine, Ichinose, Seiberg, NPB (1987)]

    $[\xi V_X]_D$ with

    $\xi = g_{\text{string}}^2 \frac{A}{192\pi^2 M_{Pl}^2}$

  - $U(1)_X$ is broken spontaneously

    $D_X = \xi + X_A A^\dagger A + \cdots$

  - $\langle A \rangle = \epsilon M_{Pl}$ is determined, with $\epsilon \sim 0.17 - 0.22$
An ambitious model

- Flavor-breaking automatically generated by string theory
- Accounts for $R$-parity (accidental, exact symmetry)
- Accounts for fermion masses (including neutrinos)
- Accounts for fermion mixings (CKM and MNS)
- Accounts for the $\mu$-term (Giudice-Masiero mechanism)
Constraints on $X$-charges

$X$-charges of matter fields have several constraints:

- Green-Schwarz anomaly cancellation relates anomaly coefficients
  
  \[
  \frac{A_{33X}}{k_3} = \frac{A_{22X}}{k_2} = \frac{A_{YYX}}{k_Y} = \frac{A_{XXX}}{3k_X} = \frac{A_{GGX}}{24}; \quad A_{YXX} = 0
  \]

- $R$-parity imposed as accidental symmetry ($B$ and $L$ don’t work)

- Yukawa textures (Froggatt-Nielsen)

\[
\begin{align*}
m_t : m_c : m_u & \sim 1 : \lambda^4 : \lambda^8 \\
m_b : m_s : m_d & \sim 1 : \lambda^2 : \lambda^4 \\
m_\tau : m_\mu : m_e & \sim 1 : \lambda^4 : \lambda^{4,5}
\end{align*}
\]
Parametrizing the Models

• All $X$-charges determined by 4 parameters
  – One is irrelevant for nucleon decay
  – 24 models specified by 3 parameters: $x, y, z$
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$$x = 0, 1, 2, 3, \quad \frac{m_b}{m_t} \sim \frac{\epsilon^x}{\tan \beta}$$
Parametrizing the Models

- All $X$-charges determined by 4 parameters
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$$y = -1, 0, 1, \quad V_{CKM} \sim \begin{pmatrix}
1 & \epsilon^{1+y} & \epsilon^{3+y} \\
\epsilon^{1+y} & 1 & \epsilon^2 \\
\epsilon^{3+y} & \epsilon^2 & 1
\end{pmatrix}$$
Parametrizing the Models

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$$z = 0, 1, \quad \frac{m_e}{m_\mu} \sim \epsilon^{2+z}, \quad U_{MNS} \sim \begin{pmatrix} 1 & \epsilon^z & \epsilon^z \\ \epsilon^z & 1 & 1 \\ \epsilon^z & 1 & 1 \end{pmatrix}$$
Parametrizing the Models

● All $X$-charges determined by 4 parameters
  – One is irrelevant for nucleon decay
  – 24 models specified by 3 parameters: $x$, $y$, $z$

● $y = 1$, $z = 0$ is compatible with $SU(5)$ invariance.

● $z = 1$ prohibits $H_u H_d$, allowing the $\mu$-term to be generated by the Giudice-Masiero mechanism.
### Example Charges

- Some charge assignments are prettier than others...

<table>
<thead>
<tr>
<th>Generation</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{Q_i}$</td>
<td>5/2</td>
<td>1/2</td>
<td>$-3/2$</td>
</tr>
<tr>
<td>$X_{L_i}$</td>
<td>13/2</td>
<td>13/2</td>
<td>13/2</td>
</tr>
<tr>
<td>$X_{U_i}$</td>
<td>5/2</td>
<td>1/2</td>
<td>$-3/2$</td>
</tr>
<tr>
<td>$X_{D_i}$</td>
<td>13/2</td>
<td>13/2</td>
<td>13/2</td>
</tr>
<tr>
<td>$X_{E_i}$</td>
<td>5/2</td>
<td>1/2</td>
<td>$-3/2$</td>
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<tr>
<td>$X_{Q_i}$</td>
<td>1399/300</td>
<td>1099/300</td>
<td>499/300</td>
</tr>
<tr>
<td>$X_{L_i}$</td>
<td>101/100</td>
<td>1/100</td>
<td>1/100</td>
</tr>
<tr>
<td>$X_{U_i}$</td>
<td>877/150</td>
<td>427/150</td>
<td>127/150</td>
</tr>
<tr>
<td>$X_{D_i}$</td>
<td>62/75</td>
<td>$-13/75$</td>
<td>$-13/75$</td>
</tr>
<tr>
<td>$X_{E_i}$</td>
<td>137/25</td>
<td>87/25</td>
<td>37/25</td>
</tr>
</tbody>
</table>

$x = 2, \ y = 1, \ z = 0, \ \Delta^H = 9$

$x = 3, \ y = 0, \ z = 1, \ \Delta^H = -1$

- ...but we’ll be guided by experiment rather than aesthetics.
Suppression of Proton Decay

- The Flavon $A$ makes operators $U(1)_X$ gauge invariant
  - $X_A = -1$
  - $q = X_{Q_i} + X_{Q_j} + X_{Q_k} + X_{L_l}$

\[
\frac{C_{ijkl}}{M_{Pl}} \left( \frac{A}{M_{Pl}} \right)^q Q_i Q_j Q_k L_l \rightarrow \frac{C_{ijkl}}{M_{Pl}} \epsilon^q Q_i Q_j Q_k L_l
\]

- $q$ determined by flavor structure only
- Coefficients determined up to order-one numbers $C_{ijkl}$
Proton Lifetime Results
Uncertainties

- Our computations suffer from two types of uncertainties

- 1: Uncertainties due to current lack of knowledge:
  - The scale of superpartner masses: $m_{\text{soft}}$
  - The hadronic matrix element $\beta_p$ from the chiral Lagrangian

- These uncertainties will be reduced once superpartners are discovered and with improved lattice calculations.

- Results just scale with input values.

\[
0.003 < \beta_p < 0.03 \text{ GeV}^3
\]

\[
\text{loop} \sim \frac{m_{\tilde{\chi}}}{m_q^2} \sim \frac{1}{m_{\text{soft}}} \Rightarrow 0.1 < m_{\text{soft}} < 10 \text{ TeV}
\]
Uncertainties

- Our computations suffer from two types of uncertainties
- 2: Uncertainties due to the effective field theory framework:
  - Unknown $\mathcal{O}(1)$ coefficients
  - Unknown relative phases

$$\frac{C_{ijkl}}{M_{Pl}} \epsilon^q Q_i Q_j Q_k L_l$$

- These coefficients can only be predicted with a more complete model of Planck scale physics.
- Parametrize ignorance by adding amplitudes **constructively**, destructively, and incoherently.

$$\Gamma = |A_1 + A_2 + A_3 + \cdots|^2$$
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$$\Gamma = |A_1|^2 + |A_2|^2 + |A_3|^2 + \cdots$$
Constraints on Models

- $p \rightarrow K^+ \bar{\nu}$ is the most constraining mode
Decay Mode Comparison

\[ \tau(p \rightarrow K^0 \mu^+) \text{ yrs} \]

\[ \tau(p \rightarrow \pi^0 e^+) \text{ yrs} \]

\[ \tau(p \rightarrow \pi^0 \mu^+) \text{ yrs} \]

\[ \beta = 0.01 \text{ GeV}^3, m_{soft} = 1 \text{ TeV}, \text{ incoherent} \]

Models

- \( x = 2 \)
- \( x = 3 \)
- \( z = 0 \) (Anarchy)
- \( z = 1 \) (Semi-Anarchy)
• **Comparison of several models:** $p \rightarrow \pi^0 \mu^+$ is a good discriminator

![Graph showing comparison of models with different parameters and experimental limits.](attachment:graph.png)
Conclusion

• Proton decay **DOES NOT** require Grand Unification.
  – SUSY models generically have $B$ and $L$ violating operators.

• $R$-parity **DOES NOT** prevent proton decay.
  – Dimension-5 operators are dangerous, even when Planck suppressed.

• A model of flavor allows predictions for proton decay.
  – Here: an ambitious, string motivated $U(1)_X$ Froggatt-Nielsen model

• Predicted rates are in the **experimentally interesting** range.
  – Proton lifetimes similar to SUSY-GUTs.

• Supersymmetry connects **Proton Decay** to Planck scale physics.