New Physics: $\mathcal{B}$ and $\mathcal{L}$ Doorways

Pavel Fileviez Perez

XI International Conference on Interconnections between Particle Physics and Cosmology
May 22nd – 26th, 2017, Texas A&M University – Corpus Christi, Texas, USA
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Status of the HEP Community
Doors to the New World (or New Physics)

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B and L Doors to New Physics

Aim:
Show that New Gauge Theories for Baryon and Lepton Numbers could change the way we think about Physics beyond the Standard Model

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The Great Desert Hypothesis

Baryon and Lepton Number Violation!

\[ \frac{c}{\Lambda^2} QQQQL \ (\tau_p > 10^{32-34} \text{ years} \implies \Lambda > 10^{15} \text{ GeV}) \]

Proton Stability

Standard Model

\[ \Lambda_{SM} \sim 100 \text{ GeV} \ (10^{-14} \text{ cm}) \]

Unified Theories, Strings?

\[ \Lambda \sim 10^{15-19} \text{ GeV} \ (10^{-29-33} \text{ cm}) \]
The Great Desert and Supersymmetry

B and L Violation:

\[ \frac{c_5}{\Lambda} \hat{Q} \hat{Q} \hat{Q} \hat{L} \ (\tau_p > 10^{32-34} \text{ years} \implies \Lambda > 10^{16-17} \text{ GeV}) \]

What about the \( \hat{L} \hat{H}_u, \hat{L} \hat{L} \hat{e}^c, \hat{Q} \hat{L} \hat{d}^c \) and \( \hat{u}^c \hat{d}^c \hat{d}^c \) interactions?

Seesaw Camel

MSSM

Unification of Gauge Couplings!

10 TeV? 100 TeV? ...

GUTs, Strings?
Spontaneous B and L Breaking!

\[ \frac{c}{\Lambda^2} QQQQL \quad (\tau_p > 10^{32-34} \text{ years} \implies \Lambda > 10^{15} \text{ GeV}) \]

The Proton is Stable!

Standard Model
\[ \Lambda_{\text{Weak}} \sim 100 \text{ GeV} \]

GUTs, Strings?
\[ \Lambda \sim 10^{15-19} \text{ GeV} \]
Outline

• Introduction
• Explicit Violation of B and L
• Spontaneous B and/or L Violation
• Summary
Introduction
B and L Numbers

**SM:** Baryon and Lepton numbers are accidental global symmetries broken by SU(2) instanton processes in 3 units.

**Theories for Physics beyond the Standard Model**

**Matter Unification:** In theories where quarks and leptons are unified one should have B or L violating interactions.

**GUTs:** In grand unified theories (SU(5), SO(10),..) B and L are explicitly broken at the high scale and generically one predicts proton decay.

**SUSY:** In the MSSM B and L are explicitly broken at the renormalizable level by RpV interactions and generically one predicts proton decay.

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\[ \mathcal{L} \supset \frac{c_L}{\Lambda_L} \ell H \ell H + \frac{c_1}{\Lambda_B^2} (\bar{u}^c \gamma^\mu q)(\bar{e}^c \gamma_\mu q) + \frac{c_2}{\Lambda_B^2} (\bar{u}^c \gamma^\mu q)(\bar{d}^c \gamma_\mu \ell) \\
+ \frac{c_3}{\Lambda_B^2} (\bar{d}^c \gamma^\mu q)(\bar{u}^c \gamma_\mu \ell) + \frac{c_4}{\Lambda_B^2} qqq\ell + \frac{c_5}{\Lambda_B^2} u^c e^c u^c d^c + \ldots \]

What are the values for \( \Lambda_L \) and \( \Lambda_B \)?

Naive bounds: \( \Lambda_L \lesssim 10^{14} \text{ GeV} \) and \( \Lambda_B \gtrsim 10^{15} \text{ GeV} \)

Maybe these operators are not present and \( \Lambda_L \) and \( \Lambda_B \) could be low!
Search for Rare Processes

- Neutrino Oscillations

- Lepton Flavour Violating Processes: $\mu \rightarrow e\gamma, \mu \rightarrow 3e, \ldots$, $\mu \rightarrow e$

- Neutrinoless double beta decay $^{A}_{Z}X \rightarrow ^{A}_{Z+2}Y + 2e^{-}$

- LNV at Colliders: $p \ p \rightarrow e_{i}^{+}e_{j}^{-}e_{k}^{+}e_{l}^{-}, \mu^{\pm}\mu^{\pm}4j, \ldots$

- Proton Decay: $p \rightarrow \pi^{0}e^{+}, K^{+}\bar{\nu}, \ldots$

- N-Nbar Oscillations

- BNV at Colliders

$U(1)_{L_{i}}$ broken!
Explicit Breaking of B and L

*Grand Unification*
Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

Our starting point is the assumption that weak and electromagnetic forces are mediated by the vector bosons of a gauge-invariant theory with spontaneous symmetry breaking. A model describing the interactions of leptons using the gauge group SU(2) \( \otimes U(1) \) was first proposed by Glashow, and was improved by Weinberg and Salam who incorporated spontaneous symmetry breaking. This scheme can also describe had-
Why the SM interactions are so different?

The strong, weak and electromagnetic interactions are just different manifestations of the same fundamental interaction at low energies!

H. Georgi, S. Glashow, 1974

$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \quad \xrightarrow{\text{SU(5)}} \quad \Lambda_{\text{Weak}} \sim 100 \text{ GeV}$

$\Lambda_{\text{GUT}} \sim 10^{15-16} \text{ GeV}$
Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

\[ G_{SM} = SU(3) \otimes SU(2) \otimes U(1) \subset SU(5) \]

\[ \alpha_3 \quad \alpha_2 \quad \alpha_1 \rightarrow \alpha_5 \]

Matter Assignment

\[ \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ -\nu \end{pmatrix}_L \quad 10 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & u_1 & d_1 \\ -u_3 & 0 & u_1^C & u_2 & u_2 \\ u_2 & -u_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^C \\ -d_1 & -d_2 & -d_3 & -e^C & 0 \end{pmatrix}_L \]

Higgs Bosons

\[ 5^H \quad 24^H \]

B and L are explicitly broken !
New Baryon and Lepton Number Violating Interactions

\[ g_5 (e^c)_L \gamma^\mu X_\mu d_L + g_5 \bar{u}_L \gamma^\mu X_\mu (u^c)_L + \text{ h.c.} \]
Proton Decay: \( \Delta B = 1, \Delta L = \text{odd} \)

\[ M_V > 10^{14-15} \text{ GeV} \]

Physics at the High Scale
Renormalizable SU(5)

\[ 5_H, 24_H, 45_H \]

This theory can be ‘tested’ or excluded at SK(HK)!

Good theory for proton decay
Minimal GUTs predict the Great Desert

Baryon and Lepton Number Violation!

\[ \frac{c}{\Lambda^2} Q Q Q L \ (\tau_p > 10^{32-34} \text{ years} \implies \Lambda > 10^{15} \text{ GeV}) \]

Proton Stability

Seesaw Camel

Standard Model
\[ \Lambda_{SM} \sim 100 \text{ GeV} \ (10^{-14} \text{ cm}) \]

Unified Theories, Strings?
\[ \Lambda \sim 10^{15-19} \text{ GeV} \ (10^{-(29-33)} \text{ cm}) \]
Spontaneous B and L Breaking!

B and L Violation:

\[ \frac{c}{\Lambda^2}_{QQQQL} \left( \tau_p > 10^{32-34} \text{ years} \right) \implies \Lambda > 10^{15} \text{ GeV} \]

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GUTs, Strings?

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Spontaneous B and L Breaking
Remark on Baryon Conservation*

A. Pais

Rockefeller University, New York, New York 10021
(Received 27 March 1973)

The Higgs mechanism can serve to implement baryon conservation via an extension of the local weak-electromagnetic gauge group by a local factor $U(1)$ without conflict with the Eötvös experiments.

(1) Charge conservation and baryon conservation are believed to be equally absolute.1 The former law emerges in the dynamical context of a strict local gauge invariance. On the other hand, no convincing dynamical framework has been found so far for baryon conservation. To be sure, one may postulate a local gauge invariance for this purpose, in straight analogy to the electromagnetic case. This implies the existence of a neutral massless vector field and of a long-range repulsive force between baryons, proportional to $\Gamma^2$.

(2) As is well known, the Abelian nature of the electromagnetic gauge group precludes any insight into the problem of why charge is quantized.7 In simplest terms, if we treat electromagnetism as a separate phenomenon, then the equality of the positron and the proton (bare) charge is to be put in by hand (after which the ratio is stable under renormalization). In the recent attempts to formulate a renormalizable unified field theory of weak and electromagnetic phenomena,8 where one assumes the existence of a local "weak-electro-
Other Results:


Breaking B and L at the TeV scale!

\[ SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L \]

where \( U(1)_B \) and \( U(1)_L \) can be broken at the TeV Scale!

How to define an anomaly free theory?
Anomaly Cancellation

Baryonic Anomalies:

\[ \mathcal{A}_1 \left( SU(3)^2 \otimes U(1)_B \right), \mathcal{A}_2 \left( SU(2)^2 \otimes U(1)_B \right), \]
\[ \mathcal{A}_3 \left( U(1)^2_Y \otimes U(1)_B \right), \mathcal{A}_4 \left( U(1)_Y \otimes U(1)^2_B \right), \]
\[ \mathcal{A}_5 \left( U(1)_B \right), \mathcal{A}_6 \left( U(1)_B^3 \right), \]

In the SM:

\[ \mathcal{A}_2 = -\mathcal{A}_3 = 3/2 \]
Different Solutions for Anomaly free theories:

- Sequential Family
- Mirror family
- Vector-like Fermions


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Main Features:

- One can have the Spontaneous Breaking of Baryon number at the Low Scale

- One predicts the existence of a leptophobic gauge boson $Z_B$

- One has a new physical Higgs called Baryonic Higgs $h_B$

- One can have a DM candidate

- A relation between the Baryon and Dark Matter Asymmetries is possible

- Since the proton is stable or highly suppressed one could have unification at the low scale in four dimensions.

P. Fileviez Perez, Physics Reports 597
Vector-like Fermions (Lepto-baryons)

<table>
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<th>Field</th>
<th>(SU(3))</th>
<th>(SU(2))</th>
<th>(U(1)_Y)</th>
<th>(U(1)_B)</th>
<th>(U(1)_L)</th>
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<td>2</td>
<td>(Y_1)</td>
<td>(B_1)</td>
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<td>(B_2)</td>
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<td>(Y_3)</td>
<td>(B_2)</td>
<td>(L_2)</td>
</tr>
</tbody>
</table>

Anomaly Cancellation: \(B_1 - B_2 = -\frac{3}{N}\),
N=1 Colorless Fields

One can define an anomaly free theory using the Fermionic Lepto-baryons:

Example: \[ \Psi_L \sim (1, 2, -1/2, B_1) \quad \Psi_R \sim (1, 2, -1/2, B_2) \]

\[ \eta_R \sim (1, 1, -1, B_1) \quad \eta_L \sim (1, 1, -1, B_2) \]

\[ \chi_R \sim (1, 1, 0, B_1) \quad \chi_L \sim (1, 1, 0, B_2) \]

\[ B_1 - B_2 = -3 \]

They can have vector-like masses and cancel all anomalies!

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Generation of Mass:

\[ \mathcal{L} \supset \lambda \psi \bar{\psi}_L \psi_R S_{BL} + \lambda \eta \bar{\eta}_R \eta_L S_{BL} + \lambda \chi \bar{\chi}_R \chi_L S_{BL} + \text{h.c.} \]

New Higgs: \[ S_{BL} \sim (1, 1, 0, -3, -3) \]

\[ \Delta B = \pm 3 \]

\( \text{Stable Proton !} \quad \text{NO DESERT !} \)
Spontaneous B and L Breaking!

\[
\frac{c}{\Lambda^2} Q Q Q L \quad (\tau_p > 10^{32-34} \text{ years} \implies \Lambda > 10^{15} \text{ GeV})
\]

The Proton is Stable!

Standard Model
\[ \Lambda_{\text{Weak}} \sim 100 \text{ GeV} \]

GUTs?
\[ \Lambda \sim 10^{15-19} \text{ GeV} \]
\[ S_{BL} \sim (1, 1, 0, -3, -3) \]

\[ \mathcal{L} \supset \frac{c}{\Lambda^{15}} (Q_L Q_L Q_L \ell_L)^3 S_{BL} \]

\[ \Delta B = \Delta L = \pm 3 \]

\[ p + p + p \rightarrow e^+ e^+ e^+ \]

\[ n + n + n \rightarrow \bar{\nu} \bar{\nu} \bar{\nu} \]

\[ p + p + n \rightarrow e^+ e^+ \bar{\nu} \]

\[ p + n + n \rightarrow e^+ \bar{\nu} \bar{\nu} \]

HIGHLY suppressed !!!
Some Features:

Dark Matter: \( \chi = \chi_L + \chi_R \) cold dark matter candidate!

Leptophobic Gauge Boson: \( Z_B \to \bar{q}q, \bar{\chi}\chi \)

New Higgs Boson: \( h_2 \to \bar{q}q, WW, ZZ, hh, \bar{\chi}\chi \)

Missing Energy at the LHC: \( pp \to Z_B h_2 \to \bar{t}t\bar{\chi}\chi \to \bar{t}t E_T^{\text{miss}} \)
Modest excess around 115 GeV with 2.9 (2.2) sigma local (global) significance

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Bounds on the Baryonic Breaking Scale


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Baryonic Dark Matter

\[ \Omega_{DM} h^2 = 0.1199 \pm 0.0027 \]

\[ g_B, M_X, M_{Z_B}, B \]

Annihilation:
\[ \bar{\chi}\chi \rightarrow Z_B \rightarrow \bar{q}q \]

Direct Detection:
\[ \chi N \rightarrow Z_B \rightarrow \chi N \]

\[ M_{Z_B} = (0.5 - 5.0) \text{ TeV} \]
\[ g_B = (0.1 - 0.5) \]

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Upper bound on the Symmetry Breaking Scale

DM relic density:

$$\Omega_{DM} h^2 \leq 0.12$$

$$v_B^2 \leq \frac{g_B^4}{\pi} \frac{\lambda^2}{(2\lambda^2 - 9g^2_B)^2 + \frac{9}{4\pi^2} g^8_B} x_f (B_1 + B_2)^2 1.77 \times 10^9 \text{GeV}^2$$

$$x_f = 20 \text{ and } B_1 + B_2 = 1/2$$

$$M_{ZB} \leq 35.3 \text{ TeV}$$

$$M_{ZB} \ll M_{GUT}$$

The Symmetry must be broken at the low scale!
What about unification?

P.F.P., M. B. Wise

B and L Violation:

\[ \frac{c}{\Lambda^2} \mathcal{QQQL} \quad (\tau_p > 10^{32-34} \text{ years} \implies \Lambda > 10^{15} \text{ GeV}) \]

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\[ \Lambda \sim 10^{15-19} \text{ GeV} \]
What is the UV completion? P.F.P., S. Ohmer,
Towards Low Scale Unification

\[ \text{SU}(4)_C \otimes \text{SU}(4)_L \otimes \text{SU}(4)_R \]

\[ \text{SU}(3)_C \otimes \text{SU}(3)_L \otimes \text{SU}(3)_R \otimes U(1)_B \]

\[ \text{SU}(3)_C \otimes \text{SU}(2)_L \otimes U(1)_Y \otimes U(1)_B \]
Summary

One can define simple theories where the Baryon and Lepton numbers are local gauge symmetries and understand the spontaneous breaking of these symmetries at the low scale.

These theories predict:

a) The proton is stable (or highly suppressed), there is NO need for the great desert, and the unification of gauge couplings could be realized at the low scale.

b) One can have a DM candidate and a consistent scenario for Baryogenesis.

c) Leptophobic gauge boson which can be light.

These theories could define a new way to think about physics beyond the Standard Model.
THANK YOU!