New Paradigm
for Baryon and Lepton Number Violation

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References:

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J. M. Arnold, P. F. P., B. Fornal, S. Spinner

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The World Largest Deserts

Deserts take up about one third (1/3) of the Earth's land surface

The Desert Hypothesis in Particle Physics

B and L Violation:

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

Standard Model

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

GUTs, Strings?

\[ \Lambda \sim 10^{15-19} \text{ GeV} \]
Unity of All Elementary-Particle Forces

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(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) ⊗ U(1) was first proposed by Glashow, and was improved by Weinberg and Salam who incorporated spontaneous symmetry breaking. This scheme can also describe hadrons of the GIM mechanism with the notion of colored quarks keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.

The next step is to include strong interactions. We assume that strong interactions are mediated by an octet of neutral vector gauge gluons associated with local color SU(3) symmetry, and that there are no fundamental strongly interacting scalar-meson fields. This insures that parity and hypercharge are conserved to order α, and does not lead to any new anomalies, so that the theory remains renormalizable. The strongest binding forces are in color singlet states which may explain why observed hadrons lie in $qqq$ and $q\bar{q}$ configurations. And, it gives another important bonus: Since the strong interactions are associated with a non-Abelian theory, they may be asymptotically free.
Hierarchy of Interactions in Unified Gauge Theories*

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(Received 15 May 1974)

We present a general formalism for calculating the renormalization effects which make strong interactions strong in simple gauge theories of strong, electromagnetic, and weak interactions. In an SU(5) model the superheavy gauge bosons arising in the spontaneous breakdown to observed interactions have mass perhaps as large as $10^{17}$ GeV, almost the Planck mass. Mixing-angle predictions are substantially modified.

The scaling observed in deep inelastic electron scattering suggests that what are usually called the strong interactions are not so strong at high energies. Asymptotically free gauge theories of the strong interactions\(^1\) provide a possible explanation: The gluon coupling constant $g(\mu)$ (defined as the value of a three-gluon or gluon-fermion-fermion vertex with momenta characterized by a mass $\mu$) is small when $\mu$ is several GeV or larger, but becomes large when $\mu$ is small, through the piling up of the logarithms encountered in perturbation theory. In one recent calculation\(^2\) a fit was found for a gauge coupling [in a color SU(3) model\(^3\)] with $g^2(\mu)/4\pi \approx 0.1$ when $\mu \approx 2$ GeV. electromagnetic\(^6\) interactions. In order to suppress unobserved interactions, Georgi and Glashow made the necessary assumption\(^7\) that some vector bosons are superheavy.

We find the notion of a simple gauge group uniting strong, weak, and electromagnetic interactions extraordinarily attractive. However, as emphasized by Georgi and Glashow, the success of any such scheme hinges on an understanding of the effects which produce the obvious disparity in strength between the strong and the weak and electromagnetic interactions at ordinary energies. We therefore wish to present in this paper a general formalism for the calculation of such effects. This will lead us to an estimate of the
The Desert Hypothesis and Supersymmetry

B and L Violation:

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

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

- Unification of Gauge Couplings!
- MSSM
- GUTs, Strings?
- LOW SCALES
- HIGH SCALES
- 10 TeV? 100 TeV?...
Apparently successful gauge theories of the strong, electromagnetic, and weak interactions have suggested that all these interactions are manifestations of a larger, encompassing gauge symmetry softly broken at a large mass scale. Models realizing this idea have been constructed.

Fusion systems which break SU(2) × U(1) symmetry at ~ 10^2 GeV have such a small mass parameter? Ordinarily mass parameters for scalar fields violate no symmetries and their smallness cannot be explained on symmetry grounds. In supersymmetric theories, where there are symmetry
**Aim:** Can we break B and L at the TeV scale?

**B and L Violation:**

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

Standard Model

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

GUTs, Strings?

\[\Lambda \sim 10^{15-19} \text{ GeV}\]
Aim

Theory for Baryon and Lepton Numbers

- Cosmology:
  - Dark Matter
  - Baryogenesis
- Neutrino Masses
- Signatures at the LHC

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Outline

• Introduction
• Living without the Great Desert
• Towards Unification and Neutrino Masses
• Summary
Introduction
Experimental Results

- Proton Decay:

\[ \Delta B = 1, \Delta L = \text{odd} \]
- Neutrino Oscillations: $\Delta L_e \neq 0, \Delta L_\mu \neq 0, \Delta L_\tau \neq 0$

Cosmology

Baryon Asymmetry: $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$

**BARYON NUMBER VIOLATION**

$\Delta B \neq 0$

Sakharov’s Condition, 1967

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Living without the Great Desert
Aim: Can we break B and L at the TeV scale?

B and L Violation:

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Standard Model
\( \Lambda_{\text{Weak}} \sim 100 \text{ GeV} \)

GUTs, Strings?
\( \Lambda \sim 10^{15-19} \text{ GeV} \)
B and L as Local Symmetries

Abraham Pais, 1973  (B as a Local Symmetry)

S. Rajpoot, 1987; Foot, Joshi, Lew, 1989

Carone, Murayama, 1995

**Breaking Local Baryon and Lepton Numbers at the TeV Scale (NO Desert !!)**

P. F. P., M.B. Wise, 2010


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!

\[ Q_L \sim (3, 2, 1/6, 1/3, 0), \quad u_R \sim (3, 1, 2/3, 1/3, 0), \quad d_R \sim (3, 1, -1/3, 1/3, 0) \]

\[ \ell_L \sim (1, 2, -1/2, 0, 1), \quad e_R \sim (1, 1, -1, 0, 1), \quad \nu_R \sim (1, 1, 0, 0, 1) \]

How to define an anomaly free theory?
Anomalies Cancellation

Baryonic Anomalies: \( A_1 \left( SU(3)^2 \otimes U(1)_B \right), A_2 \left( SU(2)^2 \otimes U(1)_B \right), \)
\( A_3 \left( U(1)^2 \otimes U(1)_B \right), A_4 \left( U(1)_Y \otimes U(1)^2_B \right), \)
\( A_5 \left( U(1)_B \right), A_6 \left( U(1)^3_B \right), \)

Leptonic Anomalies: \( A_7 \left( SU(3)^2 \otimes U(1)_L \right), A_8 \left( SU(2)^2 \otimes U(1)_L \right), \)
\( A_9 \left( U(1)^2 \otimes U(1)_L \right), A_{10} \left( U(1)_Y \otimes U(1)^2_L \right), \)
\( A_{11} \left( U(1)_L \right), A_{12} \left( U(1)^3_L \right), \)

Mixed: \( A_{13} \left( U(1)_B^2 \otimes U(1)_L \right), A_{14} \left( U(1)_B^2 \otimes U(1)_L \right), \)
\( A_{15} \left( U(1)_Y \otimes U(1)_L \otimes U(1)_B \right), \)

In the SM: \( A_2 = -A_3 = 3/2 \quad A_8 = -A_9 = 3/2 \)

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Possible Solutions

- **Sequential Family** ($B=-1, L=-3$)
- **Mirror Family** ($B=1, L=3$)
- **Vector-like Family with Seesaw**

Now they are in disagreement with LHC Constraints!

What about Fermionic Leptoquarks?
One can define an anomaly free theory using the Fermionic Lepto-quarks:

\[ \Psi_L \sim (1, 2, -1/2, B_1, L_1), \quad \Psi_R \sim (1, 2, -1/2, B_2, L_2) \]

\[ \eta_R \sim (1, 1, -1, B_1, L_1), \quad \eta_L \sim (1, 1, -1, B_2, L_2) \]

\[ \chi_R \sim (1, 1, 0, B_1, L_1), \quad \chi_L \sim (1, 1, 0, B_2, L_2) \]

\[ B_1 - B_2 = -3, \quad L_1 - L_2 = -3 \]

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

\[-\mathcal{L} \supset h_1 \bar{\Psi}_L H \eta_R + h_2 \bar{\Psi}_L \tilde{H} \chi_R + h_3 \bar{\Psi}_R H \eta_L + h_4 \bar{\Psi}_R \tilde{H} \chi_L + \lambda_1 \bar{\Psi}_L \Psi_R S_{BL} + \lambda_2 \eta_R \eta_L S_{BL} + \lambda_3 \chi_R \chi_L S_{BL} + a_1 \chi_L \chi_L S_{BL} + a_2 \chi_R \chi_R S_{BL}^\dagger + \text{h.c.} \]

\[-\mathcal{L}_\nu = Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \frac{\lambda_R}{2} \nu_R \nu_R S_L + \text{h.c.} \quad B_1 = -B_2 = -3/2 \quad L_1 = -L_2 = -3/2 \]

Higgses:

\[S_{BL} \sim (1, 1, 0, -3, -3), \quad S_L \sim (1, 1, 0, 0, -2) \]
Some Features:

Symmetry Breaking: $S_{BL} \sim (1, 1, 0, -3, -3), \quad S_L \sim (1, 1, 0, 0, -2)$

$\Delta B = \pm 3, \Delta L = \pm 2, \Delta L = \pm 3 \quad \text{NO Proton Decay!}$

Dark Matter: $\Psi^0_{LF}$ can be a cold dark matter candidate!

NO extra Flavour violation!

New Gauge Bosons: $Z_L, Z_B$
Bounds on the Baryonic Breaking Scale!

Dobrescu, Yu, PRD 88, 035021 (2013)
An, Hou, Wang, DU 2 (2013) 50

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(a) $Z'$ upper cross section limits.
**B and L Violation**

\[ S_{BL} \sim (1, 1, 0, -3, -3), \quad S_{L} \sim (1, 1, 0, 0, -2) \]

\[ \mathcal{L} \supset \frac{c}{\Lambda^{15}} (Q_{Q}Q_{Q}Q_{Q}^{}\ell_{\ell}^{})^3 S_{BL} \]

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

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

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

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

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

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Baryon Asymmetry and Dark Matter

Simple Scenario:

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

Interactions:

\[ - \mathcal{L} \supset Y_1 \bar{\Psi}_L H \eta_R + Y_2 \bar{\Psi}_R H \eta_L + Y_3 \bar{\Psi}_L \tilde{H} \chi_R \\
+ Y_4 \bar{\Psi}_R \tilde{H} \chi_L + \lambda_1 \bar{\Psi}_L \Psi_R S_B + \lambda_2 \bar{\eta}_R \eta_L S_B \\
+ \lambda_3 \chi_R \chi_L S_B + \text{h.c.} \]

Symmetries:

\[ (B - L)_{SM} \]

Sphalerons:

\[ (QQQL)^3 \bar{\Psi}_R \Psi_L. \]

\[ 3(3\mu_{u_L} + \mu_{e_L}) + \mu_{\Psi_L} - \mu_{\Psi_R} = 0. \]
\[ \Delta(B - L)_{SM} = \frac{15}{4\pi^2 g_\ast T} (12\mu_{u_L} - 9\mu_{e_L} + 3\mu_0), \]

\[ \Delta \eta = \frac{15}{4\pi^2 g_\ast T} (4\mu_{\Psi_L} + 4\mu_{\Psi_R}), \]

\[ 0 = 6\mu_{u_L} + (2B_1 - 3)\mu_{\Psi_L} + (2B_2 + 3)\mu_{\Psi_R}, \]

\[ 0 = 3\mu_{u_L} + 8\mu_0 - 3\mu_{e_L} - \mu_{\Psi_L} - \mu_{\Psi_R}, \]

\[ 0 = 9\mu_{u_L} + 3\mu_{e_L} + \mu_{\Psi_L} - \mu_{\Psi_R}. \]

\[ B_T = 0 \]

\[ Q_{em} = 0 \]

\[ B_{f}^{SM} = \frac{15}{4\pi^2 g_\ast T} (12\mu_{u_L}) \]

\[ = C_1 \Delta(B - L)_{SM} + C_2 \Delta \eta, \]

\[ |n_\chi - n_{\bar{\chi}}| \leq n_{DM} \]

\[ M_\chi \leq \frac{\Omega_{DM} C_2 M_p}{|\Omega_B - C_1 M_p \Delta n(B - L)_{SM}|}. \]
Baryonic Dark Matter

$0.10 < \Omega h^2 < 0.12$

$g_B$, $M_{Z_B}$, $M_\chi$ & $B$

Annihilation:
$\chi\chi \rightarrow Z_B \rightarrow \bar{q}q$

Direct Detection:
$\chi N \rightarrow Z_B \rightarrow \chi N$

LHC Signatures:
$pp \rightarrow Z_B \rightarrow \chi\chi$, $\bar{q}q$, $\chi\chi\bar{j}$, ..
Towards Unification and Neutrino Masses
Aim: Can we break B and L at the TeV scale?

B and L Violation:

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

Left-Right Symmetry

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

\[ SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \]

- Connection between Neutrino Masses and the Scale of Parity Violation

- Minimal Model has Type I and Type II Seesaw Mechanisms

- Doorway to SO(10) Unification

- If the scale is low one has ‘exotic’ signals at the LHC
SM Fermions:

\[ Q_L \sim (2,1,1/3,0), \ Q_R \sim (1,2,1/3,0), \ \ell_L \sim (2,1,0,1), \ \ell_R \sim (1,2,0,1) \]

Anomalies:

\[
\begin{align*}
A_1 \left( SU(2)_L^2 \otimes U(1)_B \right) &= 3/2, \\
A_2 \left( SU(2)_L^2 \otimes U(1)_L \right) &= 3/2, \\
A_3 \left( SU(2)_R^2 \otimes U(1)_B \right) &= -3/2, \\
A_4 \left( SU(2)_R^2 \otimes U(1)_L \right) &= -3/2.
\end{align*}
\]

The Simplest Solution is ..........
Type III Seesaw Fields

\( \rho_L \sim (3, 1, -3/4, -3/4), \& \rho_R \sim (1, 3, -3/4, -3/4), \)

The theory is anomaly free!

Relevant Interactions:

\[
- \mathcal{L} \supset \bar{\ell}_L \left( Y_3 \Phi + Y_4 \tilde{\Phi} \right) \ell_R \\
+ \lambda_D \left( \ell_L^T C \imath \sigma_2 \rho_L H_L + \ell_R^T C \imath \sigma_2 \rho_R H_R \right) \\
+ \lambda_\rho \ \text{Tr} \left( \rho_L^T C \rho_L + \rho_R^T C \rho_R \right) S_{BL} + \text{h.c.},
\]

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Type III Seesaw and Left-Right Symmetry

Parity Violation!

\[ v_L \ll v_R \]

\[ M_{\nu_L}^{III} \ll M_{\nu_R}^{III} \]

FIG. 1: Type III seesaw for the left-handed neutrinos.

FIG. 2: Type III seesaw for the right-handed neutrinos.
Neutrino Masses

$$- \mathcal{L}_\nu = \tilde{M}_\nu^D \bar{\nu}_L \nu_R - \frac{1}{2} M_{\nu L}^{III} \nu_L^T C \nu_L - \frac{1}{2} M_{\nu R}^{3T} C \nu_R^3 + \text{h.c.},$$

3 + 2 System

$$- \mathcal{L}_\nu = -\frac{1}{2} M_{\nu L}^{LL} \nu_L^T C \nu_L + \left( \tilde{M}_\nu^D \right)^{i\alpha} \bar{\nu}_L^i \nu_R^\alpha + \text{h.c.},$$

$$\mathcal{M}_{\nu}^{3+2} = \begin{pmatrix}
0 & 0 & 0 & m_1^D & m_2^D \\
0 & m_1 & 0 & m_3^D & m_4^D \\
0 & m_2 & m_2 & m_5^D & m_6^D \\
m_1^D & m_3^D & m_5^D & 0 & 0 \\
m_2^D & m_4^D & m_6^D & 0 & 0
\end{pmatrix}.$$
Summary

- The Desert Hypothesis plays a major role in our view of the relation between the physics at the low and high scales. However, this picture can be WRONG!

- One can define a consistent theory where $B$ and $L$ are local symmetries broken at the low scale in agreement with the experiments and there is no need to postulate the Great Desert. One has a simple theory for dark matter (and baryogenesis) which can be tested at the LHC.

- Local $B$ and $L$ Symmetries together with Left-Right Symmetry requires Type III Seesaw. The Minimal Model predicts light sterile neutrinos.
$\hat{L}H_u$, $\hat{Q}\hat{L}d^c$, $\hat{L}\hat{L}\hat{e}^c$, and $\hat{u}^c\hat{d}^c\hat{d}^c$,

For the application to Supersymmetry see:

P. F. P., M. B. Wise, JHEP 08 (2011) 068

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1310.7052
MERCI !