Leptogenesis in superstring inspired E_6 theory

Ph.D student A Kartavtsev
Supervisor E Paschos

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Motivation

◇ Baryon asymmetry of the Universe $Y_B = (0.6 - 1) \cdot 10^{-10}$

Sakharov conditions

1. Baryon (lepton) number non-conservation
2. C and CP violation
3. Deviation from thermal equilibrium

The condition is fulfilled in ...

- the standard model at quantum level (sphalerons)
- extensions of the SM with Majorana neutrinos

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The condition is fulfilled in ...

- the standard model (the CP violation is insufficient)
- extensions of the standard model

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Sakharov conditions

1. Baryon (lepton) number non-conservation
2. C and CP violation
3. Deviation from thermal equilibrium

The condition is fulfilled in ...

- the standard model (the phase transition is too weak)
- extensions of the standard model

Features of the model

◇ The E_6 model is a prominent candidate for a unified theory

Characteristic features

1. Naturally follows from breaking of superstring $E_8^{'} \otimes E_8$
2. Contains other GUT candidates as subgroups.
3. Allows chiral representations
4. Gauge anomalies are automatically canceled.

Further details ...

- chiral fields are in $N_f\mathbf{27} + \delta(\mathbf{27} + \overline{\mathbf{27}})$ representation
- gauge fields are in **78** representation

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Further details ...

- $SO(10)$ and $SU(5)$ in one breaking chain
- and $SU_R(2)$ in another breaking chain

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Apart from the known fermions 27 of E_6 fits ...

- right-handed neutrino (ν^c)
- two Higgs doublets (H^u and H^d)

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Apart from the known fermions 27 of E_6 fits ...

- new heavy down quarks (D and D^c)
- the SM singlet (S)

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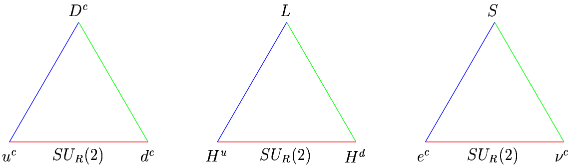
Further details ...

- in the SM cancellation of gauge anomalies is ‘accidental’

Charge assignments

◇ Embedding of the chiral fields into subgroups of E_6 is not unique



$SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U^2(1)$ intermediate symmetry

- $SU_L(2)$ doublets are Q, L, H^u and H^d
- $SU_R(2)$ doublets are (u^c, d^c), (H^u, H^d) and (e^c, ν^c)

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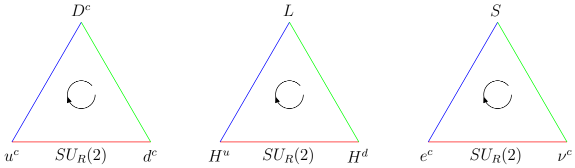

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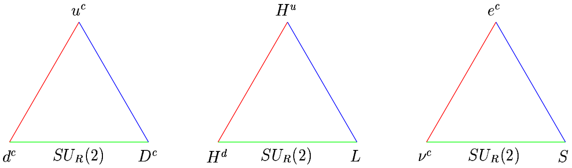

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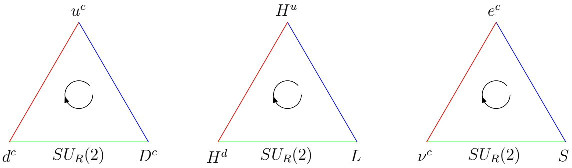

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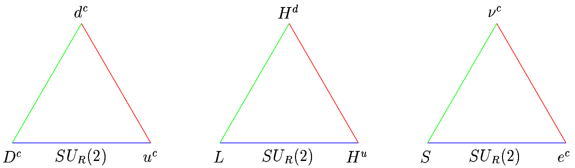

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Superpotential

◇ Superpotential of the model is given by

$$
\begin{aligned}
W \;=\;& \lambda_1 u^c (QH^u) + \lambda_2 d^c (QH^d) + \lambda_3 e^c (LH^d) \\
+\;& \lambda_4 S(H^u H^d) + \lambda_5 SDD^c \\
+\;& [\lambda_6 e^c u^c D + \lambda_7 D^c (QL) + \lambda_8 d^c \nu^c D] \\
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Responsible for ...

masses of the known fermions

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Responsible for ...

rapid proton decay mediated by new heavy down–type quark

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the neutrino mass and is required for leptogenesis

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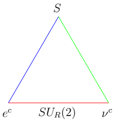

Note that ...

the same embedding into subgroups of E_6 is to be used for all generations to assure charge conservation in each vertex

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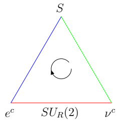

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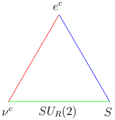

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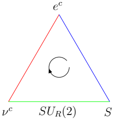

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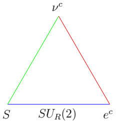

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Proton decay

◇ Gauge fields which mediate proton decay

$B-L$	Y	I_3	Q_{em}	P
-2/3	1/3	1/2	2/3	u_g
-2/3	1/3	-1/2	-1/3	d_g
2/3	5/3	1/2	4/3	X
2/3	5/3	-1/2	1/3	Y

$\Leftarrow$ new bosons which lead to rapid proton decay

$\Leftarrow$ X and Y bosons

Masses of the gauge fields

u_g and d_g masses $\propto$ to *vev* of the right–handed sneutrino

Therefore these fields ...

have to become massive at the first stage of symmetry breaking

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Masses of the gauge fields

Y boson mass is of order of EW symmetry breaking scale

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Symmetry breaking

◇ The first stage of symmetry breaking is at 10^{18} GeV

Intermediate symmetry group

1. $SU_C(3) \otimes SU_L(2) \otimes U_V(1) \otimes U_Z(1) \otimes U_{Z'}(1)$
2. $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U_{Y_L}(1) \otimes U_{Y_R}(1)$

Further details ...

- two neutral singlets ω^0 and ϕ^0
- Y_{SM} is a linear combination of Y_V, Y_Z and $Y_{Z'}$

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Further details ...

- one $SU_R(2)$ singlet ω^0 and one $SU_R(2)$ triplet $(\phi^c, \phi^0, \bar{\phi}^c)$
- Y_{SM} is a linear combination of Y_L, Y_R and I_{3R}

Breaking of $B - L$

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Further details ...

- symmetry is broken by $\langle \chi_{\nu^c} \rangle$ and $\langle \overline{\chi}_{\nu^c} \rangle$
- mass of the associated gauge field is $\sim 10^{14}$ GeV
- mass of the right–handed neutrino is $\sim 10^{11}$ GeV

∗ J. Phys. G: Nucl. Part. Phys. 31 (2005) 1191-1206.

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Cancellation of large corrections

◇ Large scale of $B - L$ breaking may bring unwanted effects

Effects associated with the scale of $B - L$ breaking

1. large Dirac mass of the conventional neutrino
2. large corrections to masses of Higgs scalars

Further details ...

- due to $\nu^c(LH^u)$ term of the superpotential

It is essential that ...

- there is a symmetry acting on right–handed neutrinos
- χ_{ν^c}, $\overline{\chi}_{\nu^c}$ and ν^c have different transformation properties

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The symmetry ensures that ...

- $B - L$ is broken at a sufficiently high scale
- χ_{ν^c} and $\overline{\chi}_{\nu^c}$ are decoupled from conventional fermions

Cancellation of large corrections

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Effects associated with the scale of $B - L$ breaking

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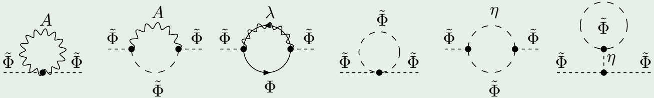
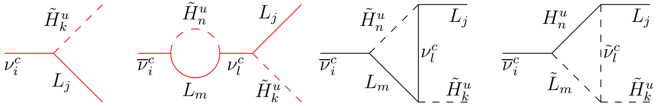
It is essential that ...

- loop corrections cancel out due to supersymmetry



Decay of heavy Majorana neutrino

◇ Tree–level and one–loop diagrams



CP asymmetry is given by ...

$$\varepsilon_s = -\frac{C_s}{16\pi} \sum_{l,m,n} \frac{\sum_{a,b;j,k} C_{a,b} \Im \left[\lambda_a^{*\,ijk} \lambda_b^{*\,imn} \lambda_b^{lmn} \lambda_a^{ljk}\right]}{\sum_{a;j,k} C_a |\lambda_a^{ijk}|} \times \frac{\sqrt{x_l}}{x_l - 1}$$

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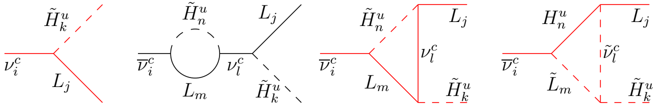

CP asymmetry is given by ...

$$\varepsilon_V = -\frac{1}{8\pi}\sum_{l,m,n}\frac{\sum_{a;j,k} C_a \Im\left[\lambda_a^{*\,ijk}\lambda_a^{*\,imn}\lambda_a^{lmk}\lambda_a^{ljn}\right]}{\sum_{a;j,k} C_a|\lambda_a^{ijk}|} \times \sqrt{x_l}\ln(1+1/x_l)$$

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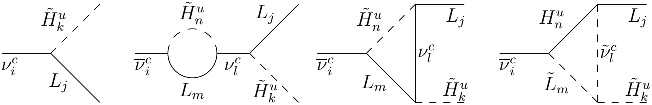
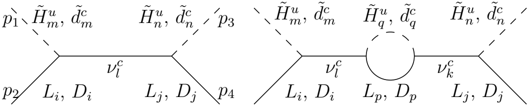


Structure of the flavor indices is not the same ...

$$\varepsilon_S \propto \Im\left[\lambda_a^{*\,ijk}\,\lambda_b^{*\,imn}\,\lambda_b^{lmn}\,\lambda_a^{ljk}\right] \text{ while } \varepsilon_V \propto \Im\left[\lambda_a^{*\,ijk}\,\lambda_a^{*\,imn}\,\lambda_a^{lmk}\,\lambda_a^{ljn}\right]$$

Two–body scattering

◇ Tree–level and one–loop diagrams



Further details ...

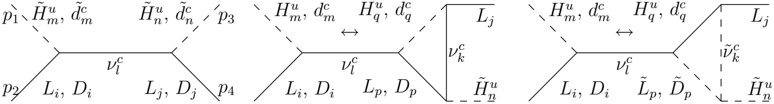
- if right–handed neutrino is on–shell then $\varepsilon_{ss} = 2\varepsilon_s$
- in thermal equilibrium generated asymmetry ε_{ss} is zero

In thermal equilibrium ...

$$\varepsilon_{ss} + \varepsilon_{sv} + \varepsilon_{us} + \varepsilon_{uv} = 0$$

Two–body scattering

◇ Tree–level and one–loop diagrams



Further details ...

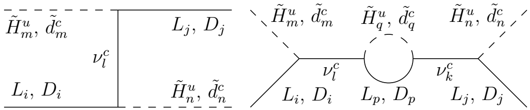
- if right–handed neutrino is on–shell then $\varepsilon_{sv} = 2\varepsilon_v$

In thermal equilibrium ...

$$\varepsilon_{ss} + \varepsilon_{sv} + \varepsilon_{us} + \varepsilon_{uv} = 0$$

Two–body scattering

◇ Tree–level and one–loop diagrams



Further details ...

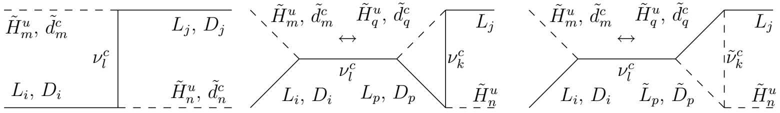
- in thermal equilibrium generated asymmetry $\varepsilon_{us} = -\varepsilon_{sv}$

In thermal equilibrium ...

$$\varepsilon_{ss}+\varepsilon_{sv}+\varepsilon_{us}+\varepsilon_{uv}=0$$

Two–body scattering

◇ Tree–level and one–loop diagrams



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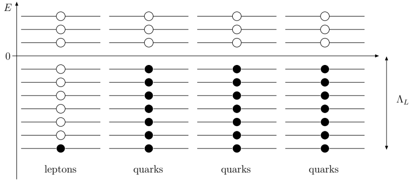
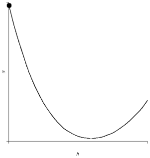
Sphalerons

◇ Sphalerons convert lepton asymmetry into baryon asymmetry





Further details ...

- $B - L$ is conserved while $B + L$ is violated
- in thermal equilibrium $3N\mu_{uL} + 2N\mu_W + \mu = 0$

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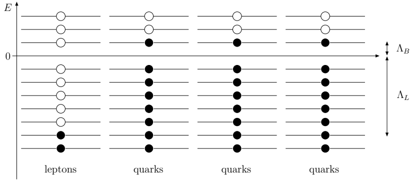

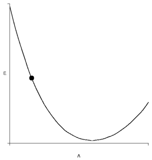

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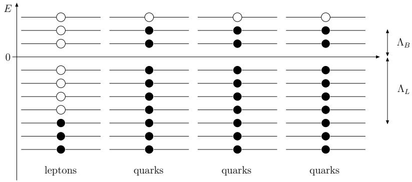

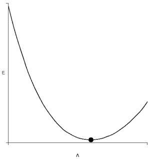

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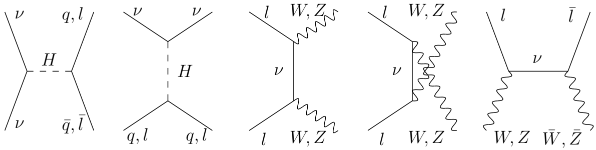
L–violating processes

◇ *Majorana* neutrino does not have a chemical potential



Lepton number is violated

1. in the helicity flipping processes mediated by neutral Higgs
2. in the scattering processes mediated by the neutrino

Rate of the processes ...

$$\gamma_s/sH \approx \gamma_t/sH \sim 10^{-13}\,(m_W/T)$$

∗ in preparation ...

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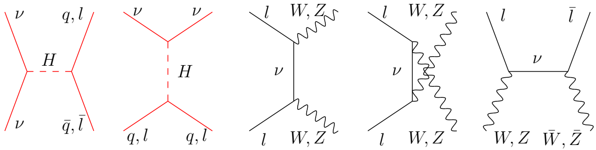

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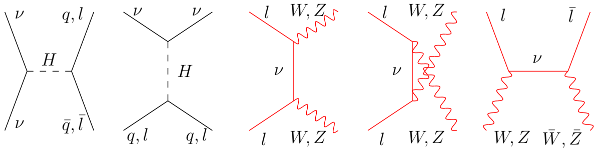

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1. in the helicity flipping processes mediated by neutral Higgs
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Rate of the processes ...

$$\gamma_s / sH \sim 10^{-15} \, (T/m_W)\,, \quad \gamma_{t+u}/sH \sim 10^{-12} \, (T/m_W)^5$$

$\ast$ in preparation ...

L–violating processes

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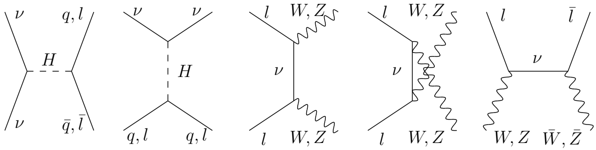

Lepton number violation

- is very small below the phase transition

Therefore ...

neutrino can be assigned an effective chemical potential

$\ast$ in preparation ...

Baryon and lepton numbers

◇ Analysis of chemical potentials yields

Baryon and lepton numbers

- $B = \frac{8N+4\bar{m}}{24N+13\bar{m}}(B-L) \approx 0.32\,(B-L)$
- $L = -\frac{16N+9\bar{m}}{24N+13\bar{m}}(B-L) \approx -0.68\,(B-L)$

Electric charges ...

- $Q_u = \frac{4\bar{m}}{24N+13\bar{m}}(B-L) \approx 0.07\,(B-L)$
- $Q_d = -\frac{8N+2\bar{m}}{24N+13\bar{m}}(B-L) \approx -0.28\,(B-L)$
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Majoron model

◇ The model introduces new scalars

$$\mathcal{L} = \frac{1}{2} M_1 \bar{N}_1 N_1^c e^{2i\frac{\phi_1}{f_1}} + \frac{1}{2} M_2 \bar{N}_2 N_2^c e^{2i\frac{\phi_2}{f_2}} + \frac{1}{2} M_3 \bar{N}_3 N_3^c e^{2i\frac{\phi_3}{f_3}}$$

Properties

1. new scalars are massless at tree–level
2. there is a new force due to scalar exchange
3. scalar masses are functions of the neutrino mass matrix

Further details ...

- the scalars acquire mass at one–loop level

$*$ in preparation ...

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Further details ...

- the force is comparable to gravity at Kpc distances

∗ in preparation ...

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Properties

1. new scalars are massless at tree–level
2. there is a new force due to scalar exchange
3. scalar masses are functions of the neutrino mass matrix

Further details ...

- properties of the neutrino and the scalars are related

∗ in preparation ...

Majoron model

◇ We require that one of the scalars is much lighter than the others

Assumptions and predictions

1. permutation symmetry in the generation space
2. normal neutrino mass hierarchy is predicted
3. neutrino mixing matrix is predicted

Further details ...

- the symmetry relates entries of the neutrino mass matrix

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Assumptions and predictions

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Further details ...

- $m_{\nu_{1,2}} \propto \lambda^2 + \epsilon^2$, $m_{\nu_3} \propto \lambda^2 + 4\epsilon^2$ if symmetry is unbroken

Majoron model

◇ We require that one of the scalars is much lighter than the others

Assumptions and predictions

1. permutation symmetry in the generation space
2. normal neutrino mass hierarchy is predicted
3. neutrino mixing matrix is predicted

Further details ...

$$\begin{pmatrix} 0.7 & 0.7 & 0 \\ 0.4 & 0.4 & 0.8 \\ 0.57 & 0.57 & 0.57 \end{pmatrix}$$ — close to the experimental matrix

Summary

1. The E_6 model
   - particle content of 27 and 78 of E_6
   - charge assignments
   - breaking of $B - L$ symmetry
2. Lepton asymmetry
   - decay of heavy Majorana neutrino
   - two–body scattering processes
3. Lepton-to-baryon number conversion
   - lepton number violation below the phase transition
   - relation among lepton and baryon numbers
4. Majoron model
   - properties of the new scalars
   - neutrino phenomenology

Future goals

1. solve the Boltzmann equations
   - reaction densities of the relevant processes
   - numerically solve the resulting set of equations
2. investigate cosmological implications of the Majoron model
   - coupling of the scalars to light and heavy neutrino
   - effects of the long–range force

Thank you for your attention