Lepton Number Violation
and the
Baryon Asymmetry of the Universe

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• The Baryon Asymmetry of the Universe
• Lepton Number Violation (LNV)
• Double Beta Decay
• LNV at the LHC
• Baryon Number Washout
• Conclusions
The Baryon Asymmetry of the Universe
Why is there something and not nothing?

Lepton Number Violation
The progress of cosmology in the last 30,000 years
Evidence for a Baryon Asymmetry

- Spectrum of anti-protons in cosmic radiation (BESS/balloon in 35 km height) **consistent with production from cosmic primaries**

- No anti-helium found (AMS spectrometers on space shuttle discovery and International Space Station ISS)
Evidence for a Baryon Asymmetry

- No traces of annihilation radiation in the local galaxy cluster
- No distortion of the cosmic microwave background
Size of the Baryon Asymmetry

- **Big Bang Nucleosynthesis**: synthesis of $p, n \rightarrow D, ^3He, ^4He, ^7Li$
  
  depends on baryon and radiation density

$$\eta_B = \frac{n_B - n_B}{n_\gamma}$$

- **CMB**: comparing heights 1st peak (gravitation $\rightarrow$ gas) vs. 2nd peak (gravitation $\leftrightarrow$ gas)

$$\eta_B^{obs} = (6.20 \pm 0.15) \times 10^{-10}$$
Baryogenesis

- Baryon Asymmetry as initial condition?
- **Cosmic inflation:** \( a(t) \sim \exp \left( \frac{\Lambda}{3} t \right) \)
  - Universe flat, homogenous and empty
  - Necessity of Baryogenesis after reheating

- **3 Sakharov conditions:**
  - Non-Equilibrium
  - C and CP violation
  - Baryon Number Violation

- Prominent example – **Leptogenesis:** right-handed neutrino decay in early Universe

\[ \text{[Fukugita, Yanagida, 1986]} \]
Sphalerons: **B-Violation within the Standard Model**

Topologically different field configurations $\Rightarrow$ degenerate vacua with different baryon numbers [t’Hooft, 1976]

$T > T_{EW} \Rightarrow$ Transitions between vacua, $B+L$ Violation

[Kuzmin, Rubakov, Shaposhnikov, 1985]
Baryogenesis

- Electroweak baryogenesis via Sphalerons?
  In the SM: EW phase transition not rapid enough (non-equilibrium), 2 competing vacua during phase transition necessary → depends on Higgs quartic coupling → only possible for Higgs masses < 70 GeV

- Physics beyond SM needed!

- Leptogenesis: B–L Asymmetry + B+L violating Sphalerons ⇒ B Asymmetry
Baryogenesis

Not simple:

“Das Nichts nichtet - the Nothing noths”

(Martin Heidegger)

BUT: This is **NO** talk on Baryogenesis!

So let’s assume we somehow created a Baryon Asymmetry and let’s go on with particle physics
Why is Lepton Number Violation interesting?
Takaaki Kajita of the University of Tokyo and Arthur B. McDonald of Queen’s University in Ontario were awarded the Nobel Prize in Physics on Tuesday for discovering that the enigmatic subatomic particles known as neutrinos have mass.
"Uncharacteristically for a physics conference people gave the speaker a standing ovation. I stood up too. Having survived every experimental challenge since the late 1970s the Standard Model had finally fallen. The results showed that at the very least the theory is incomplete."

Hitoshi Murayama (UC Berkeley) about the Neutrino-98-Konferenz
Bullshit ?
Why is LNV interesting?

Why is a non-zero $\nu$ mass physics beyond SM?

EITHER - OR

1. $m_D \bar{\nu}_L \nu_R$
2. $m_M \bar{\nu}_R^c \nu_R$
3. $m_M \bar{\nu}_L^c \nu_L$

Lepton Number (Violation) is at the core of the link between $\nu$ mass & physics beyond SM!
Key Message

Lepton Number Violation
Key Message

0νBB Decay  →  Lepton Number Violation  →  Baryon Asymmetry of the Universe

LHC
Double Beta Decay
Probing LNV

Most prominent: $0v\beta\beta$ decay

$\nu = \nu$

$d \rightarrow u$

$W^\pm$

$U_{ei}$

$p_L \frac{m_i + q^+}{q^2 - m_i^2} P_L$

$d \rightarrow u$

$W^\pm$

$U_{ei}$

$\sim m_\nu$

“Mass Mechanism”

General Case

Lepton Number Violation
What is $0\nu\beta\beta$ decay?

$$2n \rightarrow 2p + 2e^-$$

Mass mechanism:

$$[T_{1/2}^{0\nu}]^{-1} \propto \left| \sum_i U_{ei}^2 m_i \right|^2$$

In general: Every operator

$$\bar{p} \bar{p} e^+ e^- nn/M^5$$

will generate $0\nu\beta\beta$ decay
0νBB Decay

\[ \text{0νββ} \]

\[ \text{= (a)} \quad \text{+ (b)} \quad \text{+ (c)} \quad \text{+ (d)} \]


Lepton Number Violation
0νBB Decay

\[ \sim m_\nu \]

\[ \sim \varepsilon \]

\[ \sim \varepsilon^2 \]

Pointlike @ nuclear Fermi momentum \( O(r_N^{-1}) \sim 100 \text{ MeV} \)

General parametrization for $0\nu\beta\beta$ Decay

Long-Range Part

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left\{ j_{V-A}^\mu J_{V-A,\mu}^\dagger + \sum_{\alpha,\beta} \epsilon_{\alpha}^\beta j_{\alpha}^\mu J_{\alpha}^\dagger \right\}$$

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{V+A}$</td>
<td>$4.4 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$\epsilon_{V-A}$</td>
<td>$7.0 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$\epsilon_{S^+P}$</td>
<td>$1.1 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\epsilon_{S^-P}$</td>
<td>$1.1 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\epsilon_{TR}$</td>
<td>$6.4 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>$\epsilon_{TR}$</td>
<td>$1.7 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

$$\mathcal{O}_{V-A} = \gamma^\mu (1 - \gamma_5)$$
$$\mathcal{O}_{V+A} = \gamma^\mu (1 + \gamma_5)$$
$$\mathcal{O}_{S-P} = (1 - \gamma_5)$$
$$\mathcal{O}_{S+P} = (1 + \gamma_5)$$

$$\mathcal{O}_{TL} = \frac{i}{2} [\gamma_{\mu}, \gamma_{\nu}] (1 - \gamma_5)$$

$$\mathcal{O}_{TR} = \frac{i}{2} [\gamma_{\mu}, \gamma_{\nu}] (1 + \gamma_5).$$

[HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, PLB 1999]
General parametrization for 0νBB Decay

Short-Range Part

\[ \mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \left\{ \epsilon_1 J J j + \epsilon_2 J_{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_{\mu\nu} j^\nu + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J_j \right. \\
+ \epsilon_6 J^\mu J^\nu j_{\mu\nu} + \epsilon_7 J J_{\mu\nu} j_{\mu\nu} + \epsilon_8 J_{\mu\alpha} J^{\nu\alpha} j_{\nu} \left. \right\}, \]

| | $|\epsilon_1|$ | $|\epsilon_2|$ | $|\epsilon_3|$ | $|\epsilon_4|$ | $|\epsilon_5|$ |
|---|---|---|---|---|---|
| | $3 \cdot 10^{-7}$ | $2 \cdot 10^{-9}$ | $4 \cdot 10^{-8}$ | $1 \cdot 10^{-8}$ | $2 \cdot 10^{-8}$ | $2 \cdot 10^{-7}$ |

[HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, PLB 2001]
LNV at the LHC
0νBB - LHC Complementarity

\[
\text{pointlike @ nuclear Fermi momentum } O(r_N^{-1}) \approx 100 \text{ MeV}
\]

\[
d = 9 \text{ operator} \\
\text{TeV scale particles} \\
\text{New Physics} @ \text{the LHC!}
\]

\[
0νBB - \text{LHC Complementarity!}
\]
0νBB @ LHC: Example RPV SUSY

Like-Sign Di-Lepton Signal:
10 fb⁻¹, √s = 14 TeV
SM + SUSY Background

\[ M_{1/2} = 300 \text{ GeV} + 0.6M_0 \]

[Allanach, Kom, HP, PRL 2009]
Also, e.g.
Left-Right Symmetry:

[Keung, Senjanovic 1983; Nemevsek, Nesti, Senjanovic, Tello 2001]

Model-independent approach also for LNV@LHC?

- Necessary to go beyond effective field theory approach of [HP, Hirsch, Kovalenko, Klapdor–Kleingrothaus, PLB 1999]
- Open up vertices, systematic decomposition of the $d=9$ 0νBB operator [Bonnet, Hirsch, Ota, Winter, 2013]
Systematic decomposition of 0vBB Decay

2 Topologies:

- Fermion
  - Scalar or Vector
  - Go through all gauge invariant possibilities giving rise to $\bar{u} u \bar{e} e d d \frac{1}{M^5}$ [Bonnet, Hirsch, Ota, Winter, 2013]

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Topologies I and II
Model independent approach to 0νBB @LHC

Apply the decomposition of [Bonnet, Hirsch, Ota, Winter, 2013] to 0νBB @ LHC:

- Results for Scalars and Vectors very similar
- Concentrate on Scalars & Topology 1:

\[ S_{\text{charge}}, \]
\[ S_{\text{LQ, charge}}^{L} (L \neq 0, B \neq 0), \]
\[ S_{\text{DQ, charge}}^{B} (B = \pm 2/3) \]

[Helo, Hirsch, Kovalenko, HP, 2013]
$0
\nu\beta\beta$ versus LHC SSD at $\sqrt{s} = 14$ TeV

$0\nu\beta\beta$ - grey & blue areas: present bound, $T_{1/2} > 10^{26}\text{y}$ (smallest rate operator)

$T_{1/2} > 10^{26}\text{y}, T_{1/2} > 10^{27}\text{y}$ (largest rate operator)

$$\mathcal{A}_{0\nu\beta\beta} \propto \frac{g_1g_2g_3g_4}{m_{S_1}^2 m_{\psi q} m_{S_3}^2} \equiv \frac{g_{\text{eff}}^4}{M_{\text{eff}}^5}.$$ 

LHC: curved lines
dashed: $\text{Br}^{\text{eff}}(S \rightarrow eejj) = 10^{-2}$
solid: $\text{Br}^{\text{eff}}(S \rightarrow eejj) = 10^{-1}$

[Helo, Hirsch, Kovalenko, HP, 2013]
Discriminating 0νββ mechanisms: Charge Asymmetry

Moreover: LHC can discriminate contributions

- Invariant mass peaks (s-channel: $m^2_{eejj} = m^2_S$)
- Charge asymmetry (due to different numbers of $u, d, u^c, d^c$ in p and different diagrams)

$0\nu\beta\beta$ vs LHC sensitivities

→ with the exception of Leptoquarks:

LHC more sensitive than $0\nu\beta\beta$ Decay!

$0\nu\beta\beta$ signal → LHC signal

No LHC signal → no $0\nu\beta\beta$ signal

- OR -

$0\nu\beta\beta$ is Long Range (e.g. mass-mechanism)

→ how to find out?
A major problem

Uncontroversial detection of $0\nu\beta\beta$ decay: uttermost importance!

- prove lepton number to be broken in Nature
- prove neutrinos to be Majorana particles  Schechter and Valle, 1982

However: it will immediately generate another puzzle:

which mechanism that triggers the decay?

Without identification of the underlying mechanism:

- experimental evidence for $0\nu\beta\beta$ decay will only provide ambiguous information about the concrete physics underlying the decay!
- No information about $m_\nu$ can be obtained from a measurement of the neutrinoless double beta decay half life!
Big question:

what is it?
Half life ratios

- Concentrate on: different mechanisms result in different NMEs
- Problem: smaller NME for e.g. the mass mechanism as compared to any alternative new physics mechanism can be compensated by a larger value for the neutrino mass
- However: If one mechanism dominates $\rightarrow \langle m_\nu \rangle$ or $\epsilon_{NP}$ drops out in the ratio of experimentally determined half lives for two different emitter isotopes

$$\frac{T_{1/2}(^AX)}{T_{1/2}(^{76}\text{Ge})} = \frac{|M(^{76}\text{Ge})|^2 G(^{76}\text{Ge})}{|M(^AX)|^2 G(^AX)}$$

- $\Rightarrow$ Half life ratios depend on the mechanism of double beta decay, but not on the new physics parameter!
- Compare with theoretical prediction for different mechanisms!
- Error in NME ratio can be reduced compared to theoretical error in one matrix element (cancellations of systematic effects)!
Half life ratios: Results


Matrix elements calculated in the QRPA approach of
or taken from literature using the same code
Half life ratios: results

- $\bar{\beta}_P$ SUSY contributions:
  similar and rather small deviations
  Most effectively discriminated by comparing $^{82}\text{Se}$ and $^{136}\text{Xe}$ (60% variation)

- Left-right symmetric models:
  strong deviations for $\lambda\lambda$ combination, comparing $^{128}\text{Te}$ and $^{150}\text{Nd}$:
  \[ \frac{T_{1/2}^{LR}}{T_{1/2}^{m_N}}[^{128}\text{Te}] \gtrsim 20 \times \frac{T_{1/2}^{LR}}{T_{1/2}^{m_N}}[^{150}\text{Nd}] \]
  small deviations for $\eta\eta$ combination comparison of $^{100}\text{Mo}$ and $^{136}\text{Xe}$ yields a variation of 70 %

- Extra-dimensional neutrino models with a large brane shift parameter:
  large deviations for $^{136}\text{Xe}$ and $^{150}\text{Nd}$:
  \[ \frac{T_{1/2}^{KK}}{T_{1/2}^{m_N}}[^{150}\text{Nd}] \gtrsim 5 \times \frac{T_{1/2}^{KK}}{T_{1/2}^{m_N}}[^{100}\text{Mo}] \]

Caution: strong deformation of $^{150}\text{Nd}$ is ignored in most QRPA calculations
→ Simkovic, Pacearescu, Faessler, 2004
Nuclear matrix element uncertainties

- **Theoretical errors** of NME calculation dominate experimental errors ⇒ difficult to determine the confidence level with which either mechanism can be excluded to generate the observed double beta evidence!

- Assuming e.g. a statistical distribution of matrix element values ⇔ relative variation of 60% in $R^{NP}(A \ X)$ w.r.t. $R^{\nu\nu}(A \ X)$ is significant only if NMEs would be known with an accuracy of 15%! → unrealistic!

- Estimates of uncertainties vary: factor 3-5 (spread of published values) to only 30% (uncertainties inherent in QRPA) Rodin, Faessler, Simkovic, Vogel, 2006

**However:**

- significance will increase if a whole set of measurements in different isotopes resembles the expected pattern

- **systematical effects** (like a too small $g_{pp}$ in the pn-QRPA approach, a different $g_{A}$, higher-order terms, different model-space) will cancel out

- → check results with alternative codes!

- → include pion exchange which may be dominating in some of the models discussed!
0νββ: Pinning down the mechanism

Possibilities to disentangle at least some of the possible mechanisms:

- **analysis of angular correlations** between the emitted electrons
  → few experiments sensitive to electron tracks

- **comparative study of 0νββ and 0νβ+ with electron capture (EC) decay**
  Hirsch, Muto, Oda, Klapdor-Kleingrothaus, 1994
  → small rates and experimental challenge to observe the produced X-rays or Auger electrons

- **study of double beta decay to excited 0+ states**
  Simkovic, Nowak, Kaminski, Raduta, Faessler, 2001
  → few experiments sensitive to transitions to excited states.

[F. Deppisch +Super-NEMO, 2010]
Moreover: LHC can discriminate contributions

- Invariant mass peaks (s-channel: $m^{2}_{eejj} = m^{2}_{S}$)
- Charge asymmetry (due to different numbers of $u, d, u^{c}, d^{c}$ in $p$ and different diagrams)

What’s the connection with Baryogenesis?
Baryon Number Washout
“Falsifying Leptogenesis at the LHC”

[F. Deppisch, J. Harz, M. Hirsch, PRL 112 (2014) 221601]

“Falsifying Leptogenesis at the LHC”

- LNV @ LHC
- Lower bound on washout of Lepton Number Asymmetry
- No out–of–equilibrium condition in early universe!
But **EVEN WORSE**: consider Sphalerons

Leptogenesis:

\[ \nu_R \text{ decay} \]

\[ B-L \]

\[ B+L \text{ Sphalerons} \]

B Asymmetry

In Reverse:

\[ B-L \text{ e.g. LHC} \]

\[ B+L \text{ Sphalerons} \]

B washout
Large LNV @ LHC (or elsewhere) will washout ANY pre-existing Baryon Asymmetry, irrespective of the Baryogenesis mechanism (Leptogenesis, etc...)

Original Paper: [Fukugita, Yanagida, 1990]

“Sphaleron induced Baryon Number Non-conservation and a constraint on Majorana neutrino masses”

Also:

[Gelmini, Yanagida, 1992] keV-bound on ν mass
[Klapdor-Kleingrothaus, Kolb, Kuzmin, 1990] Bound on sneutrinos
[Hollenberg, HP, Schalla, 2011] Bound on 4th generation neutrinos
[...many others]
Conclusions I

- OR -

0νBB

Long range mechanism e.g. $m_\nu$

Short range mechanism

LNV @ LHC

[Deppisch, Harz, Hirsch, Huang, HP, 2015]

Low-Scale Baryogenesis

also detectable @ LHC?

“2 for one”
If $0\nu\text{BB}$

High scale baryogenesis $\rightarrow$ LNV @ LHC $\rightarrow$ If $0\nu\text{BB}$

Mass mechanism $m_\nu$

Very probably high scale origin of $m_\nu$

[Deppisch, Harz, Hirsch, Huang, HP, 2015]
But:

0νBB probes LNV only for the electron flavor!

How to close this Flavor Loophole?
Closing the flavor loophole: combine 0vBB and LFV

Washout processes are in Thermal equilibrium for:

\[
\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H} \frac{T^{2D-4}}{\Lambda_D^{2D-8}} = c'_D \frac{\Lambda_{\text{Pl}}}{\Lambda_D} \left( \frac{T}{\Lambda_D} \right)^{2D-9} \gtrsim 1, \quad (8)
\]

with \( c'_D = \pi^2 c_D / (3.3 \sqrt{g_*}) \approx 0.3 c_D \). This is the case in the temperature interval

\[
\Lambda_D \left( \frac{\Lambda_D}{c'_D \Lambda_{\text{Pl}}} \right)^{\frac{1}{2D-9}} \equiv \lambda_D \lesssim T \lesssim \Lambda_D. \quad (9)
\]

[Deppisch, Harz, Hirsch, Huang, HP, 2015]
**Outlook**

**Outlook:** closing the flavor loophole

**combine 0νBB and LFV**

Washout intervals:
- lower bound: equilibrium
- upper bound: EFT breakdown

\[
T_{1/2} = 2.1 \times 10^{25} \text{ y}
\]

An asymmetry generated at scales above \( \lambda \) will be washed out if 0νBB is observed

[Deppisch, Harz, Hirsch, Huang, HP, 2015]
Washout processes are in Thermal equilibrium for:

\[
T_{1/2} = 2.1 \times 10^{25} \, y \cdot \left( \frac{\Lambda_D}{\Lambda_D^0} \right)^{2d - 8}
\]

[Deppisch, Harz, Hirsch, Huang, HP, 2015]
Summary

$0^{\nu BB}$

- EITHER -

$LNV@LHC \rightarrow$ Low scale Baryogenesis, “2 for 1”

- OR -

very probably high-scale origin of $m_{\nu}$

(like vanilla type-I seesaw + leptogenesis)

[Deppisch, Harz, Hirsch, Huang, HP, 2015]

Loopholes exist and should be checked!

(Flavor restriction, conserved charges, etc...)

[Deppisch, Harz, Hirsch, 2014; Antaramian, Hall, Rasin, 1994...]

Heinrich Päs