Neutrinoless Double Beta Decay and Baryogenesis

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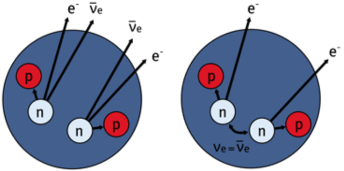
- neutrinos - neutral, left-handed, massive, light ...
- $\implies$ problem of the Standard Model (SM)
- Dirac or Majorana nature?
- Majorana masses $\iff$ LNV $\iff$ neutrinoless double beta decay ($0\nu\beta\beta$)
- massive right-handed neutrinos (seesaw mechanism) $\implies$ leptogenesis
- LNV at low and high energies - interplay?

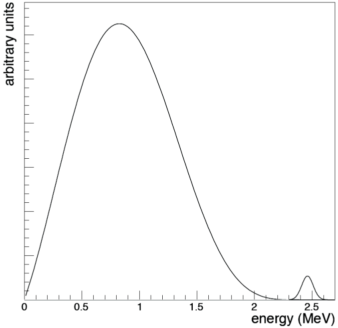
Neutrinoless Double Beta Decay

UCL

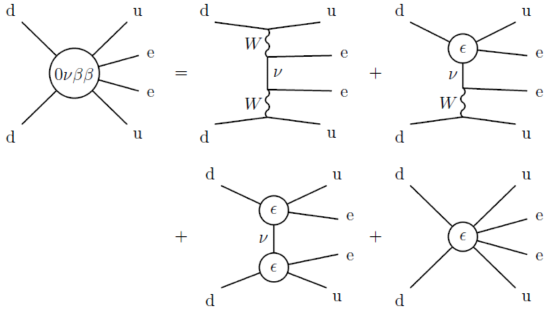
- current limit: $T_{1/2}^{^{76}Ge} > 2.1 \times 10^{25}$ y (GERDA)

  $T_{1/2}^{^{136}Xe} > (1.1 - 1.9) \times 10^{25}$ y (EXO 200, KamLAND-Zen)
- future experimental sensitivity: $T_{1/2} \sim 10^{27}$ y





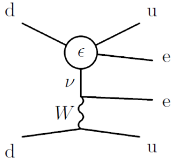
- $\mathcal{L}_{0\nu\beta\beta} = \mathcal{L}_{LR} + \mathcal{L}_{SR}$, general Lagrangian in terms of effective couplings ϵ corresponding to the pointlike vertices at the Fermi scale



  - F. F. Deppisch, M. Hirsch, H. Päs: *Neutrinoless Double Beta Decay and Physics Beyond the Standard Model*, J. Phys. G **39** (2012), 124007

- long-range part: $\mathcal{L}_{LR} = \frac{G_F}{\sqrt{2}}\left[J^\dagger_{V-A_\mu} j^\mu_{V-A} + \tilde{\sum}_{\alpha,\beta} \epsilon^\beta_\alpha J^\dagger_\alpha j_\beta\right]$,

  where $J^\dagger_\alpha = \bar{u}O_\alpha d$, $j_\beta = \bar{e}\mathcal{O}_\beta \nu$ and $\mathcal{O}_{V\pm A} = \gamma^\mu(1\pm\gamma_5)$,
  $\mathcal{O}_{S\pm P} = (1\pm\gamma_5)$,
  $\mathcal{O}_{T_{R,L}} = \frac{i}{2}[\gamma_\mu, \gamma_\nu](1\pm\gamma_5)$



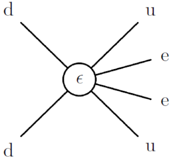
Isotope	$\lvert\epsilon^{V+A}_{V-A}\rvert$	ϵ^{V+A}_{V+A}	ϵ^{S+P}_{S-P}	ϵ^{S+P}_{S+P}	ϵ^{TR}_{TL}	ϵ^{TR}_{TR}
^{76}Ge	3.3×10^{-9}	5.9×10^{-7}	1.0×10^{-8}	1.0×10^{-8}	6.4×10^{-10}	1.0×10^{-9}

- connection to the experimental half-life: $T^{-1}_{1/2} = \lvert\epsilon^\beta_\alpha\rvert^2 G_i \lvert M_i\rvert^2$
- $\implies$ $0\nu\beta\beta$ half-life sets constraints on effective couplings

- short range part:

$$L_{SR} = \frac{G_F^2}{2m_p}\left[\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\mu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right],$$

where $J = \bar{u}(1 \pm \gamma_5)d$,
$J^{\mu} = \bar{u}\gamma^{\mu}(1 \pm \gamma_5)d$,
$J^{\mu\nu} = \bar{u}\frac{i}{2}[\gamma^{\mu}, \gamma_{\nu}](1 \pm \gamma_5)d$
$j = \bar{e}(1 \pm \gamma_5)e^C$
$j^{\mu} = \bar{e}\gamma^{\mu}(1 \pm \gamma_5)e^C$



Isotope	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz(RRz)}\rvert$	$\epsilon_3^{LRz(RLz)}$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
^{76}Ge	3.0×10^{-7}	1.7×10^{-9}	2.1×10^{-8}	1.3×10^{-8}	1.4×10^{-8}	1.4×10^{-7}

LNV Effective Operators

- a wide range of effective operators violating lepton number
- odd dimension: $5, 7, 9, 11, \ldots$
  - A. de Gouvea, J. Jenkins: *A Survey of Lepton Number Violation Via Effective Operators*, Phys. Rev. D **77** (2008), 013008

$\mathcal{O}$	Operator	$m_{\alpha\beta}$	Λ_ν (TeV)	Best Probed	Disfavored
4_a	$L^iL^j\overline{Q}_i\bar{u^c}H^k\epsilon_{jk}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}$	4×10^9	$\beta\beta0\nu$	U
4_b	$L^iL^j\overline{Q}_k\bar{u^c}H^k\epsilon_{ij}$	$\frac{y_u g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^6	$\beta\beta0\nu$	U
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$	U
6	$L^iL^j\overline{Q}_k\bar{u^c}H^lH^k\overline{H}_i\epsilon_{jl}$	$\frac{y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$	U
7	$L^iQ^j\bar{e^c}\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$	$y_{\ell_\beta}\frac{g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^2	mix	C
8	$L^i\bar{e^c}\bar{u^c}d^cH^j\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	mix	C
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	3×10^3	$\beta\beta0\nu$	U
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^3	$\beta\beta0\nu$	U
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_d^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	30	$\beta\beta0\nu$	U
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^4	$\beta\beta0\nu$	U
12_a	$L^iL^j\overline{Q}_i\bar{u^c}\overline{Q}_j\bar{u^c}$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^7	$\beta\beta0\nu$	U
12_b	$L^iL^j\overline{Q}_k\bar{u^c}\overline{Q}_l\bar{u^c}\epsilon_{ij}\epsilon^{kl}$	$\frac{y_u^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$	U
13	$L^iL^j\overline{Q}_i\bar{u^c}L^le^c\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^5	$\beta\beta0\nu$	U
14_a	$L^iL^j\overline{Q}_k\bar{u^c}Q^kd^c\epsilon_{ij}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$	U
14_b	$L^iL^j\overline{Q}_i\bar{u^c}Q^ld^c\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$	U
15	$L^iL^jL^kd^c\overline{L}_i\bar{u^c}\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$	U
16	$L^iL^je^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC	U
17	$L^iL^jd^cd^c\bar{d^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC	U
18	$L^iL^jd^cu^c\bar{u^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC	U

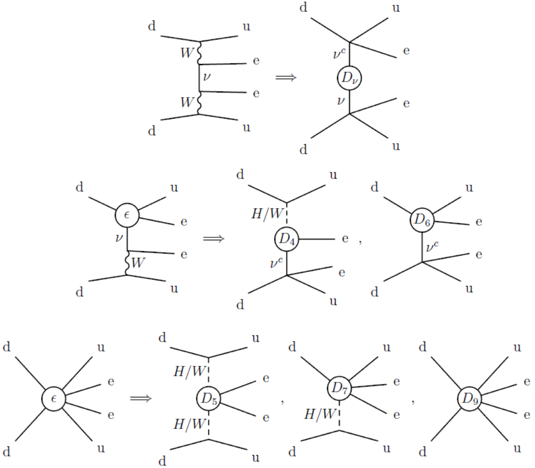
- so far, focus on 4 examples of various dimensionalities:

$$\begin{aligned}
\mathcal{O}_5 &= \frac{1}{\Lambda_5}(L^i L^j) H^k H^l \varepsilon_{ik}\varepsilon_{jl}, \\
\mathcal{O}_7 &= \frac{1}{\Lambda_7^3}(L^i d^c)(\bar{e^c}\bar{u^c}) H^j \varepsilon_{ij}, \\
\mathcal{O}_9 &= \frac{1}{\Lambda_9^5}(L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}), \\
\mathcal{O}_{11} &= \frac{1}{\Lambda_{11}^7}(L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \varepsilon_{jk}\varepsilon_{lm}.
\end{aligned}$$

- $\mathcal{O}_5$ is Weinberg operator, other represent non-standard $0\nu\beta\beta$ decay mechanisms

LNV Effective Operators

- LNV operators can contribute to $0\nu\beta\beta$ decay at various levels



Lorentz Structure & Fierz Transformations

- LNV operators can acquire various Lorentz structures
- we are interested in contractions corresponding to terms in $0\nu\beta\beta$ decay Lagrangian $\mathcal{L}_{0\nu\beta\beta}$ (convention)
- we want to describe all the possible Fierz transformations of these contractions
- $\implies$ to list all the possible independent realizations triggering $0\nu\beta\beta$ decay
- standard definition of Fierz transformation:

$$\left(\bar{\psi}_1\Gamma_a\psi_2\right)\left(\bar{\psi}_3\Gamma_b\psi_4\right) = \sum_{c,d} F_{abcd}\left(\bar{\psi}_1\Gamma_c\psi_4\right)\left(\bar{\psi}_3\Gamma_d\psi_2\right),$$

where the coefficients are given by

$$F_{abcd} = \frac{1}{16}\mathrm{Tr}[\Gamma_a\Gamma_d\Gamma_b\Gamma_c]. \tag{1}$$

Lorentz Structure & Fierz Transformations

- LNV effective operators in terms of Weyl spinors
- $\Longrightarrow$ either 2D Fierz transformations or 4D ones + chiral projectors $R = \frac{1}{2}(1+\gamma_5)$ and $L = \frac{1}{2}(1-\gamma_5)$
- e.g. Fierz transformation for 2D spinors transforming scalar current to vector current:

$$(z_1 z_2)(\bar{z}_3 \bar{z}_4) = \frac{1}{2}(\bar{z}_3 \sigma^\mu z_2)(\bar{z}_4 \sigma_\mu z_1)$$

- applied on $\mathcal{O}_7$:

$$\begin{aligned} \mathcal{O}_7 &= \frac{1}{\Lambda_7^3}(d^c L^i)(\bar{e^c}\bar{u^c})H^j \varepsilon_{ij} \\ &\rightarrow \mathcal{O}_7^{(\mathrm{vec})} = \frac{1}{2\Lambda_7^3}(\bar{e^c}\sigma^\mu L^i)(\bar{u^c}\sigma^\mu d^c)H^j \varepsilon_{ij}. \end{aligned}$$

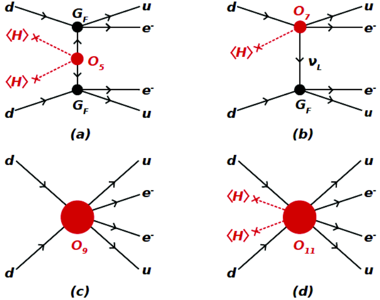
- goal: algorithmic automation, useful not only for this project

- contributions to $0\nu\beta\beta$ decay generated by the LNV effective operators in terms of effective vertices, point-like at the nuclear Fermi level scale

- if $0\nu\beta\beta$ is observed, the scale of the underlying operator can be determined

- $m_e \epsilon_{\mathcal{O}5} = \frac{v^2}{\Lambda_5}, \quad \frac{G_F \epsilon_{\mathcal{O}7}}{\sqrt{2}} = \frac{v}{2\Lambda_7^3}$

- $\frac{G_F^2 \epsilon_{\{\mathcal{O}9, \mathcal{O}11\}}}{2 m_p} = \left\{ \frac{1}{\Lambda_9^5}, \frac{v^2}{\Lambda_{11}^7} \right\}$



$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik} \epsilon_{jl},$$
$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c} \bar{u^c}) H^j \epsilon_{ij},$$
$$\mathcal{O}_9 = (L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}),$$
$$\mathcal{O}_{11} = (L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk} \epsilon_{lm}$$

Baryon Asymmetry

- observed baryon asymmetry → asymmetry in primordial matter and antimatter
- $\eta_b^{\rm obs} = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$
- beyond Standard Model (BSM) generation mechanism
- popular mechanism: leptogenesis

Baryogenesis: Sakharov Conditions

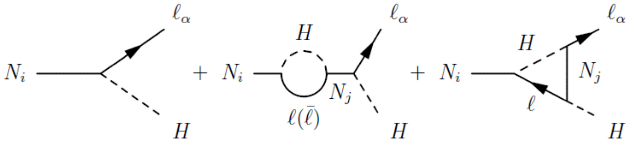
1. baryon number violation
2. C and CP violation (otherwise baryon number is still conserved)
   - $\Gamma(X \to B + Y) - \Gamma(\overline{X} \to \overline{B} + \overline{Y}) \neq 0$
3. interactions out of thermal equilibrium, otherwise $\langle B \rangle = 0$
   - odd under CPT transformation

$$\langle B \rangle = \mathrm{Tr}[e^{-\frac{H}{T}} B] = \mathrm{Tr}[\theta^{-1}\theta e^{-\frac{H}{T}} B] = \mathrm{Tr}[e^{-\frac{H}{T}} \theta B \theta^{-1}] = -\langle B \rangle_T$$

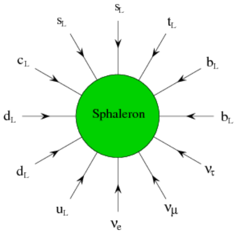
- heavy neutrino N decays out of equilibrium to leptons and antileptons unevenly
  - M. Fukugita, T. Yanagida: *Baryogenesis Without Grand Unification*, Phys. Lett. B **174** (1986), p. 45

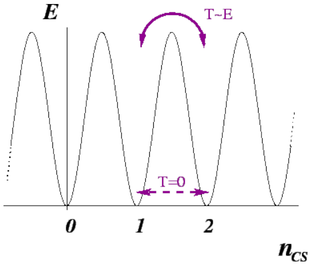
$$\varepsilon_{1CP} = \frac{\sum_\alpha \left(\Gamma(N_1 \to L_\alpha H) - \Gamma(N_1 \to \overline{L_\alpha} H^*)\right)}{\sum_\alpha \left(\Gamma(N_1 \to L_\alpha H) + \Gamma(N_1 \to \overline{L_\alpha} H^*)\right)}$$

- contributing processes:



- the asymmetry in the lepton sector can be converted into baryon asymmetry via *sphaleron processes*
  - F. R. Klinkhamer, N. S. Manton: *A saddle-point solution in the Weinberg-Salam theory*, Phys. Rev. D **30** (1984), p. 2212–2220
- tunnelling between different vacua, Chern-Simons winding number of the field configuration
- $100 \lesssim T \lesssim 10^{12}$ GeV





Boltzmann Equations

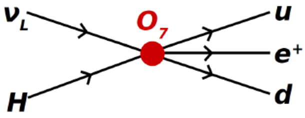
- calculation of particle number densities in the early universe

- $zHn_\gamma \frac{\mathrm{d}\eta_N}{\mathrm{d}z} = -\sum_{a,i,j,\dots} [Na \cdots \leftrightarrow ij \cdots]$,
  where $z = \frac{m}{T}$, $\eta_N = \frac{n_N}{n_\gamma}$, $H \sim \frac{T^2}{\Lambda_{Pl}}$ (Hubble parameter)

- $$[Na \cdots \leftrightarrow ij \cdots] = \frac{n_N n_a \cdots}{n_N^{eq} n_a^{eq} \cdots} \gamma^{eq}(Na \cdots \to ij \cdots) - \frac{n_i n_j \cdots}{n_i^{eq} n_j^{eq} \cdots} \gamma^{eq}(ij \cdots \to Na \cdots)$$

Washout Effects

- processes that equilibrate species $\iff$ 3rd Sakharov condition violated
- for the $\mathcal{O}_7$ operator there are 20 possible washout interactions of type $2 \leftrightarrow 3$, the $1 \leftrightarrow 4$ processes are phase-space suppressed



- $\mathcal{O}_7 = \frac{1}{\Lambda^3}\left(L^i d^c\right)\left(\bar{e^c}\bar{u^c}H^j\epsilon_{ij}\right)$
- Boltzmann equation: $n_\gamma H T \frac{\mathrm{d}\eta_L}{\mathrm{d}T} = c_7 \frac{T^{10}}{\Lambda_7^6}\eta_L$
- $\frac{\Gamma_W}{H} \equiv \frac{c_7}{n_\gamma H}\frac{T^{10}}{\Lambda_7^6} = c_7' \frac{\Lambda_{Pl}}{\Lambda_7}\left(\frac{T}{\Lambda_7}\right)^5$
- from calculation of the scattering density $c_7 = \frac{27}{2\pi^7}$

Washout Effects

- washout is effective if: $\dfrac{\Gamma_W}{H} = c'_D \dfrac{\Lambda_{Pl}}{\Lambda_D} \left(\dfrac{T}{\Lambda_D}\right)^{2D-9} \gtrsim 1$

- if $0\nu\beta\beta$ is observed $\implies$ lepton number asymmetry washed out in temperature interval:

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

- solving the Boltzmann equation $\implies$ scale $\hat{\lambda}_D$, above which a maximal lepton asymmetry of 1 is washed out to η_b^{obs} or less

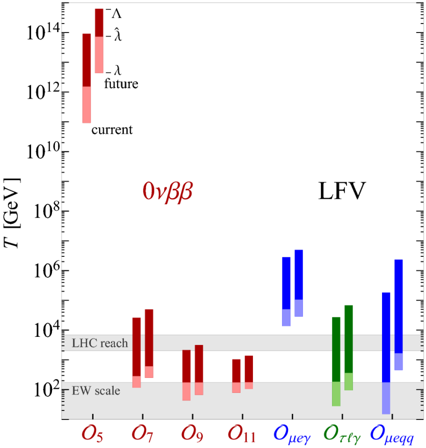
$$\hat{\lambda}_D \approx \left[(2D-9)\ln\left(\frac{10^{-2}}{\eta_b^{\text{obs}}}\right)\lambda_D^{2D-9} + v^{2D-9}\right]^{\frac{1}{(2D-9)}}$$

Lepton Flavour Violation (LFV)

- so far: washout just in e sector (from $0\nu\beta\beta$), no info on μ, τ
- now also: $0\nu\beta\beta$ operators + lepton flavour violation operators
- we focus on conversion given by processes $l_i \to l_j + \gamma$ and $\mu \to e$ conversion in nuclei
- experimental limits: $\mathrm{Br}_{\mu \to e\gamma} < 5.7 \times 10^{-13}$, $\mathrm{Br}_{\tau \to \ell\gamma} < 4.0 \times 10^{-8}$ (with $\ell = e, \mu$) and $\mathrm{R}^{\mathrm{Al}}_{\mu \to e} < 7.0 \times 10^{-13}$
- $\Longrightarrow$ if also LFV processes are observed, lepton asymmetry can no longer be stored in another flavour sector

Results

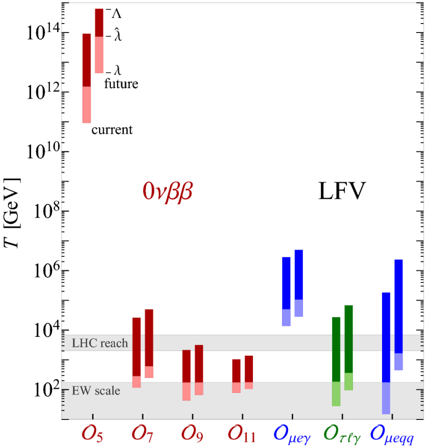
- big gap between Weinberg operator $\mathcal{O}_5 \approx 10^{14}$ GeV and other LNV operators $\approx 10^{3-4}$ GeV
- $\mathcal{O}_7$ corresponds to a final state of opposite electron chiralities
- $\implies$ can be distinguished by SuperNEMO from the purely left-handed current interaction via the measurement of the decay distribution



- R. Arnold et al. (NEMO-3): *Search for Neutrinoless Double-Beta Decay of 100Mo with the NEMO-3 Detector*, Phys.Rev. D **89** (2014), 111101

Results

- the stringent bound $\mu \to e^+\gamma$ means a high cut-off scale, since does not overlap with $0\nu\beta\beta$ operators
- $\tau \to \mu/e + \gamma$ and $\mu \to e$ can be combined with $0\nu\beta\beta$ operators
- $\mathcal{O}_9$ and $\mathcal{O}_{11}$ can be probed at the LHC



Caveats

1. Certain mechanism protecting the asymmetries from washouts can exist. For instance, the $B + aL$ conservation and $U(1)_Y$ gauge symmetry protection.

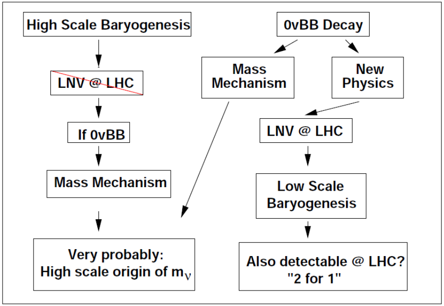
2. Baryon asymmetry can be generated below the electroweak scale, where the sphaleron processes are not efficient. Therefore, although the lepton asymmetry can be still washed out, it does not mean the washout of baryon asymmetry.

Conclusions

- Observation of a non-standard $0\nu\beta\beta$ mechanism would imply that highscale baryogenesis is generally excluded and it is likely to occur at a low scale, under the electroweak scale.

- A high scale baryogenesis would mean that the only manifestation of LNV at low scales is $0\nu\beta\beta$ through the standard mass mechanism (Weinberg operator $\mathcal{O}_5$).

- This would also imply that the origin of neutrino mass lies very probably at a high scale.



Thank You for attention

...soon after the first observation of a non-standard $0\nu\beta\beta$ decay...