Neutrinoless Double Beta Decay

Destructive interference in $(\beta\beta)_{0\nu}$-decay

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Based on the work of S.Pascoli, J.Lopez-Pavon, S.Wong

Overview

- Introduction
  - The importance of$(\beta\beta)_{0\nu}$-decay
  - The experimental status of $(\beta\beta)_{0\nu}$-decay
  - Different physical mechanisms for $(\beta\beta)_{0\nu}$-decay
- The Relation Between ν Mass Generation and $(\beta\beta)_{0\nu}$-Decay
- Potential Destructive Interference and Future Measurements
- Conclusion

Introduction

Introduction — The importance of $(\beta\beta)_{0\nu}$-decay

ν oscillation proves that ν have masses.

We need to identify the nature of ν — Dirac VS Majorana.
Moreover, the oscillations only tells us the mass square differences of neutrinos:

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U^*_{\alpha,k} U_{\beta,k} U_{\alpha,j} U^*_{\beta,j} \exp(-i \frac{\Delta m^2_{kj} L}{2E}),$$

but we also need to know

- the absolute mass scale $(m_1,\ m_2,\ m_3)$
- the type of hierarchy (the sign of Δm^2_{31})

The neutrino can be

Dirac Particle $\Rightarrow \nu \neq \overline{\nu} \Rightarrow$ Lepton number conserved or
Majorana Particle $\Rightarrow \nu = \overline{\nu} \Rightarrow$ Lepton number violated

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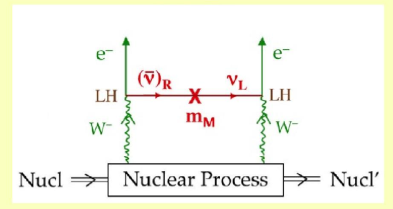
The most sensitive process to test the nature of ν :

$$\boxed{(A,Z) \rightarrow (A,Z+2) + 2\,e^-}$$



Introduction — The experimental status of $(\beta\beta)_{0\nu}$-decay

We have not observed any signal from $(\beta\beta)_{0\nu}$-decay experiments yet.

The best present measurements on the $T_{1/2}$ of $(\beta\beta)_{0\nu}$-decay

Experiments	Isotope	The limit of $T_{1/2}$ (years)	$< m_{\beta\beta} >$ (meV)
HM	^{76}Ge	$> 1.9 \times 10^{25}$	< 220 - 410
NEMO-3	^{100}Mo	$> 5.8 \times 10^{23}$	< 610 - 1280
	^{82}Se	$> 2.1 \times 10^{23}$	< 1160 - 2170
CUORICINO	^{130}Te	$> 3 \times 10^{24}$	< 290 - 570
DAMA	^{136}Xe	$> 4.5 \times 10^{23}$	< 1140 - 2680

(A.S.Barabash **arXiv:0807.2948**. The $< m_{\beta\beta} >$ limits correspond to QPRA nuclear matrix elements)

but many new experiments will start soon.

The next-generation and next-to-next generation $(\beta\beta)_{0\nu}$-decay experiments.

Experiments	Isotope	Mass of Isotope (kg)	Sensitivity of $T_{1/2}$ (years)	Sensitivity of $m_{\beta\beta}$ (meV)
CUORE	^{130}Te	200	6.5×10^{26}	20 - 50
(2013)			2.1×10^{26}	35 - 90
GERDA	^{76}Ge	40	2×10^{26}	70 - 300
(2011)		1000	6×10^{27}	10 - 40
MAJORANA	^{76}Ge	30-60	$1 - 2 \times 10^{26}$	70 - 300
(2013)		1000	6×10^{27}	10 - 40
EXO	^{136}Xe	200	6.4×10^{25}	95 - 220
(2011)		1000	8×10^{26}	27 - 63
SuperNEMO	^{82}Se	100-200	$1 - 2 \times 10^{26}$	40 - 100
(Proposal)				

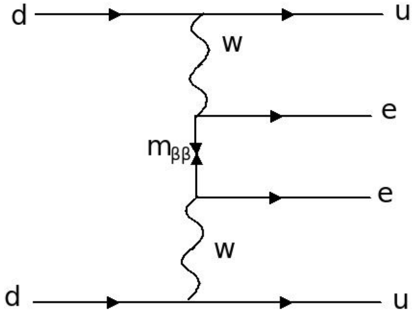
(A.S.Barabash **arXiv:0807.2948**)

(S.R.Elliott **arXiv:1203.1070**)

Introduction — Different physical mechanisms for $(\beta\beta)_{0\nu}$-decay

$(\beta\beta)_{0\nu}$-decay can be induced by various lepton-number violating (LNV) mechanisms:

- (i) by exchange of light Majorana neutrinos;



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- (i) by exchange of light Majorana neutrinos;

$$[T^{0\nu}_{1/2}]_i^{-1} = G_i \mid \frac{< m_{\beta\beta} >}{m_e} \mathcal{M}_{\nu,i} \mid^2$$

$$< m_{\beta\beta} > = \sum_j \mid (\mathrm{U^L_{ej}}) \mid^2 e^{i\alpha_j} \mathrm{m_j}$$

where i stands for the nuclear species, $< m_{\beta\beta} >$ is the effective neutrino mass.

G_i and $\mathcal{M}_\nu$ are the phase space factor and nuclear matrix element of light ν mechanism.

	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te
$G_i \times 10^{15}$ yr	7.93	35.2	57.3	55.4
$\mathcal{M}_\nu$	5.82	5.66	5.15	4.70

E.Lisi et al. **arXiv:1103.2504**

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- (ii) by exchange of heavy Majorana neutrinos (mass > 100 MeV);

$$[T^{0\nu}_{1/2}]_i^{-1} = G_i \mid \sum_j^{\text{heavy}} (V^L_{ej})^2 \frac{m_p}{M_j} \mathcal{M}_{N,i} \mid^2$$

where i stands for the nuclear species, V^L_{ej} corresponds to the heavy (sterile) neutrino(s) mixing.

G_i and $\mathcal{M}_N$ are the phase space factor and nuclear matrix element of heavy ν mechanism.

	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te
$G_i \times 10^{15}$ yr	7.93	35.2	57.3	55.4
$\mathcal{M}_N$	412	408	404	384

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Introduction — Different physical mechanisms for $(\beta\beta)_{0\nu}$-decay

$(\beta\beta)_{0\nu}$-decay can be induced by various lepton-number violating mechanisms:

- (i) by exchange of light Majorana neutrinos;
- (ii) by exchange of heavy Majorana neutrinos (mass $>$ 100 MeV);
- (iii) by R-parity violating mechanism;
- etc.

Relation between ν Mass Generation and $(\beta\beta)_{0\nu}$-Decay

Firstly, we concentrate our discussion on the exchange of **light neutrino** and **heavy neutrino** mechanism.

$$[T^{0\nu}_{1/2}]^{-1}_i = G_i \mid \eta_\nu \mathcal{M}_{\nu,i} + \eta_N \mathcal{M}_{N,i} \mid^2,$$

- i stands for different nuclei. **The values of $\mathcal{M}_\nu$, $\mathcal{M}_N$ and G depend on nuclei**.
-

$$\eta_\nu = \frac{1}{m_e} \sum_j^{\text{light}} (U^L_{ej})^2 m_j = \frac{< m_\nu >}{m_e}, \quad \text{(light } \nu \text{ LNV parameter)}$$

$$\eta_N = m_p \sum_j^{\text{heavy}} (V^L_{ej})^2 \frac{1}{M_j} \qquad \text{(heavy } \nu \text{ LNV parameter)}$$

Constraints from Seesaw Mechanism

The heavy ν contribution is sub-dominant due to the constraints from Seesaw Mechanism on the ν masses.
Due to the diagonalization of ν mass matrix,

$$U^* \mathrm{diag}(m_1, m_2, ..., m_n) U^\dagger = \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}$$

$$\Downarrow$$

$$\sum_k^{\text{light}} (U_{ek})^2 m_k + \sum_j^{\text{heavy}} (V_{ej})^2 M_j = 0,$$

(M.Blennow et al. **arXiv:1005.3240**)
Hence the decay rate can be rewritten as

$$[T_{1/2}^{0\nu}]^{-1} = G_i \mid \frac{\sum_j (V_{ej})^2 M_j}{m_\mathrm{e}} \mathcal{M}_{\nu,i} \cdot (-1 + \frac{m_\mathrm{e} m_\mathrm{p}}{M_j^2} \frac{\mathcal{M}_{N,i}}{\mathcal{M}_{\nu,i}}) \mid^2,$$

which is dominated by the standard light ν mechanism if the heavy ν masses M_j are large.

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The possibility of significant contribution from heavy ν

Exceptions.

However, there are some exceptions.

If neutrino masses are not generated at tree level but loop level, then the Seesaw constraint does not apply.

One of the example for generating negligible tree level ν mass is Extended Seesaw with two heavy ν

(S.K.Kang and C.S.Kim **arXiv:hep-ph/0607072**)

$$M = \begin{pmatrix} 0 & m_D^T & \epsilon m_D'^T \\ m_D & \mu' & \Lambda^T \\ \epsilon m'_D & \Lambda & \mu \end{pmatrix}$$

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the corresponding tree level active ν mass is given by

$$m_{\mathrm{tree}} = (m_D \frac{\mu}{\Lambda^2} m_D) - \epsilon(m_D' \frac{1}{\Lambda} m_D + m_D \frac{1}{\Lambda} m_D')$$

m_{tree} vanishes if $\mu = 0$ and $\epsilon = 0$,

which means

$$< m_{\beta\beta} > \equiv (m_{\mathrm{tree}})_{ee} = 0$$

at tree level.

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at tree level.

$$\cancel{\sum_k^{\text{light}} (U_{ek})^2} m_k + \sum_j^{\text{heavy}} (V_{ej})^2 M_j \neq 0,$$

Thus in our model, the light ν mechanism contribute to $(\beta\beta)_{0\nu}$-decay through loop level mass

loop level ν mass.

$$\delta M_L = \frac{g^2}{(64\pi^2)c_w^2} U_L^* \hat{M}^3 \left(\frac{3\ln(\frac{\hat{M}^2}{m_z^2})}{\frac{\hat{M}^2}{m_z^2} - 1} + \frac{\ln(\frac{\hat{M}^2}{m_h^2})}{\frac{\hat{M}^2}{m_h^2} - 1} \right) U_L^\dagger = \mathrm{f}(\mu', \Lambda, m_D)$$

where $\hat{M}$ is the diagonalization of mass matrix M. U_L corresponds to the mixing matrix.

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where $\hat{M}$ is the diagonalization of mass matrix M. U_L corresponds to the mixing matrix.

New Decay Rate.

$$[T^{0\nu}_{1/2}]_i^{-1} = G_i \left| \frac{\delta M_L}{m_{\mathrm{e}}} \mathcal{M}_{\nu,i} + m_{\mathrm{p}} \sum_j^{\mathrm{heavy}} (V_{ej})^2 \frac{1}{M_j} \mathcal{M}_{N,i} \right|^2 .$$

The contributions of two mechanisms would not suffer the constraint as before and are possible to be of similar order.

Potential Destructive interference in $(\beta\beta)_{0\nu}$-decay

Destructive interference in $(\beta\beta)_{0\nu}$-decay

The contributions from different mechanisms may be of similar order, and they may even **destructively interfere with each other**.
For example, the absence of evidence for $(\beta\beta)_{0\nu}$-decay in ^{76}Ge may due to the **destructive interference**.

$$\Gamma_{Ge} = G_{Ge} \mid \eta_\nu M_{\nu,Ge} + \eta_N M_{N,Ge} \mid^2 = 0,$$

$$\Rightarrow \eta_N = -\eta_\nu \times \frac{M_{\nu,Ge}}{M_{N,Ge}} = -\frac{|< m_\nu >|}{m_e} \times \frac{M_{\nu,Ge}}{M_{N,Ge}}.$$

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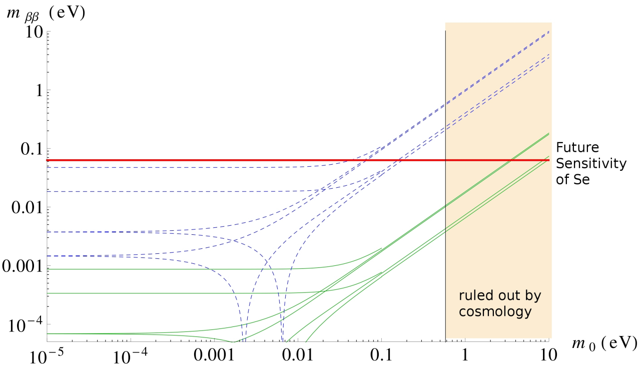
$$\Rightarrow \eta_N = -\eta_\nu \times \frac{M_{\nu,Ge}}{M_{N,Ge}} = -\frac{|< m_\nu >|}{m_e} \times \frac{M_{\nu,Ge}}{M_{N,Ge}}.$$

However, the cancellation effect is different for different nuclei, since the ratio of $\frac{M_\nu}{M_N}$ depends on the nuclear species.

$$\begin{aligned}\Gamma_i &= G_i \mid \eta_\nu M_{\nu,i} + \eta_N M_{N,i} \mid^2 \\ &= G_i \times (\frac{|< m_\nu >|}{m_e})^2 |M_{\nu,i}|^2 \cdot \mid 1 - \frac{M_{\nu,Ge}}{M_{N,Ge}} \frac{M_{N,i}}{M_{\nu,i}} \mid^2.\end{aligned}$$

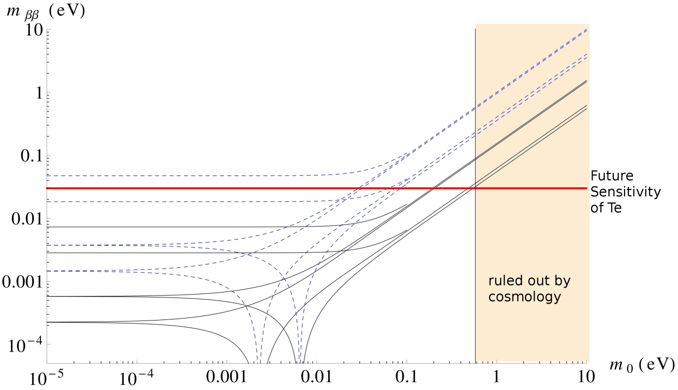
Assuming full cancellation in ^{76}Ge, the $m_{\beta\beta}$ of ^{82}Se becomes



| $m_{\beta\beta}$ | of ^{82}Se under different mechanisms.

- The green solid lines — the destructive interference between light and heavy neutrino;
- The blue dashed lines —"only light neutrino contribution";

Assuming full cancellation in ^{76}Ge, the $m_{\beta\beta}$ of ^{130}Te becomes



| $m_{\beta\beta}$ | of ^{130}Te under different mechanisms.

- The black solid lines — the destructive interference between light and heavy neutrino;
- The blue dashed lines —“only light neutrino contribution”;

Conclusion

Conclusion

- A signal in present or future $(\beta\beta)_{0\nu}$-decay experiments implies the existence of **Majorana neutrinos** and **Lepton Number Violation**.
- The measurement of decay rate can provide information about the ν **mass scale and its mass hierarchy**.
- Still need to identify the contributions from different mechanisms.
- **The destructive interference** may play an important role since it reduces the decay rate even by orders of magnitude than previously expected (in the assumption of "no interference"). The effect can be significantly different in various nuclei.
- **Due to the possibility of destructive interference, the absences of observation in some of the future experiments do not prove that neutrino is a Dirac particle. We have to check the decays of different isotope before making any conclusions.**

Thank You

Appendix

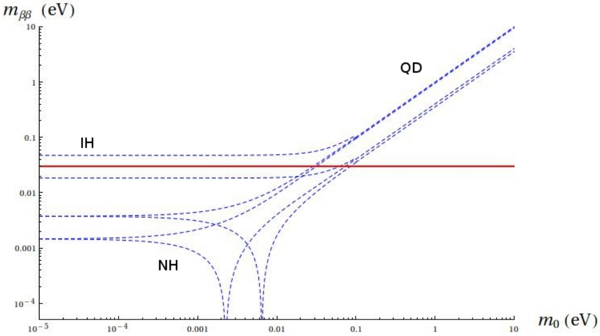
A Dirac particle cannot mediate such a process.

What is the physics implication of $(\beta\beta)_{0\nu}$-decay?

- $(\beta\beta)_{0\nu}$-decay requires that at least one neutrino = its anti-neutrino, which leads to lepton number violation (LNV).
- LNV is crucial in leptogenesis and generating the baryon asymmetry of the Universe.
- Seesaw mechanism predicts the existence of Majorana neutrinos. The observation of $(\beta\beta)_{0\nu}$-decay may not help confirming Seesaw directly, but it can put this hypothesis in favor.
- The observation of $(\beta\beta)_{0\nu}$-decay can also help us to estimate the scale of neutrino masses and determine the mass hierarchy.

The relation between $(\beta\beta)_{0\nu}$-decay and neutrino mass

Since $[T^{0\nu}_{1/2}]^{-1} \propto |< m_{\beta\beta} >|^2$.



m_0 is the minimum of (m_1, m_2, m_3) under different hierarchy

Appendix

- Light ν : $\eta_\nu \propto |<m_\nu>|$.
  The contribution is suppressed by the lightness of active neutrinos

- Heavy ν : $\eta_N \propto \sum_i^{\text{heavy}} (V_{ei}^L)^2 \frac{1}{M_i}$.
  The contribution is suppressed by both the heavy ν mass and the weak active-sterile neutrino mixing

Light ν domination

Hence the decay rate can be rewritten as

$$\begin{aligned}
[T^{0\nu}_{1/2}]^{-1} &= G_i \mid \frac{1}{m_\mathrm{e}} \sum_k^{\text{light}} (U_{ek})^2 m_k \mathcal{M}_{\nu,i} + m_\mathrm{p} \sum_j^{\text{heavy}} (V_{ej})^2 \frac{1}{M_j} \mathcal{M}_{N,i} \mid^2 \\
&= G_i \mid (-\sum_j (V_{ej})^2 M_j) \frac{\mathcal{M}_{\nu,i}}{m_\mathrm{e}} + \sum_j (V_{ej})^2 M_j \frac{m_\mathrm{p}}{M_j^2} \mathcal{M}_{N,i} \mid^2 \\
&= G_i \mid \frac{\sum_j (V_{ej})^2 M_j}{m_\mathrm{e}} \mathcal{M}_{\nu,i} \cdot (-1 + \frac{m_\mathrm{e} m_\mathrm{p}}{M_j^2} \frac{\mathcal{M}_{N,i}}{\mathcal{M}_{\nu,i}}) \mid^2,
\end{aligned}$$

which is dominated by the standard light ν mechanism if the heavy ν masses M_j are large.

Appendix

$$M = \begin{pmatrix} 0 & m_D^T & \epsilon m_D'^T \\ m_D & \mu' & \Lambda^T \\ \epsilon m_D' & \Lambda & \mu \end{pmatrix}$$

$$\delta M_L = \frac{g^2}{(64\pi^2)c_w^2} U_L^* \hat{M}^3 \left(\frac{3\mathrm{Ln}(\frac{\hat{M}^2}{m_z^2})}{\frac{\hat{M}^2}{m_z^2} - 1} + \frac{\mathrm{Ln}(\frac{\hat{M}^2}{m_h^2})}{\frac{\hat{M}^2}{m_h^2} - 1} \right) U_L^\dagger \neq 0$$

$$A_{\mathrm{light}} = \frac{\delta M_L}{m_{\mathrm{e}}} \mathcal{M}_{\nu,i}$$

$$A_{\mathrm{heavy}} = m_{\mathrm{p}} \frac{m_D^2 \mu'}{(m_D^2 + \Lambda^2)^2} \mathcal{M}_{N,i}$$

Appendix

The new constraint between light ν and heavy ν contribution.

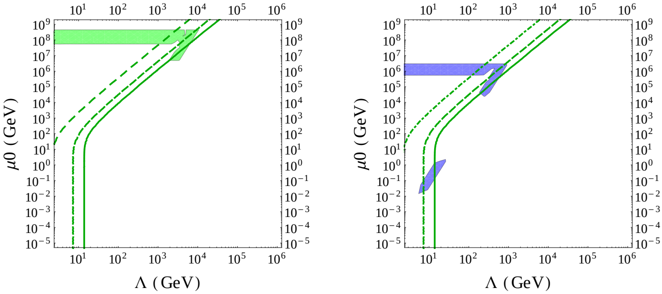
In our model, the mass matrix should be rewritten as

$$M = \begin{pmatrix} 0 & m_D^T & \epsilon m_D'^T \\ m_D & \mu' & \Lambda^T \\ \epsilon m_D' & \Lambda & \mu \end{pmatrix} + \begin{pmatrix} \delta M_L & \delta m_D^T & \delta(\epsilon m_D'^T) \\ \delta m_D & \delta\mu' & \delta\Lambda^T \\ \delta(\epsilon m_D') & \delta\Lambda & \delta\mu \end{pmatrix}$$

Thus $\sum_k^{\mathrm{light}} (U_{ek})^2 m_k + \sum_j^{\mathrm{heavy}} (V_{ej})^2 M_j = \delta M_L \neq 0$

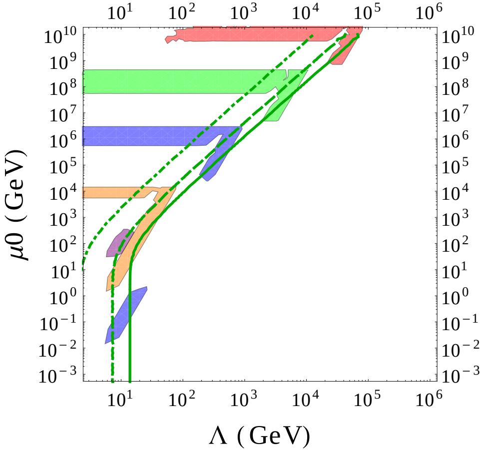
This relation implies that $\sum_j^{\mathrm{heavy}} (V_{ej})^2 M_j \approx 0$,

but in $(\beta\beta)_{0\nu}$-decay,
the contribution of heavy ν $(A_{\mathrm{heavy}}) \propto \sum_j (V_{ej})^2 \frac{1}{M_j^2} \neq 0$ and can still be large.



The allowed parameter regions (colored areas) which satisfy the constraints of different neutrino experimental constraints. The green lines correspond to the ratio of $r \equiv |A_{\rm heavy}/A_{\rm light}| = 1$ (solid), 10 (dashed) and 1000 (dot-dashed).

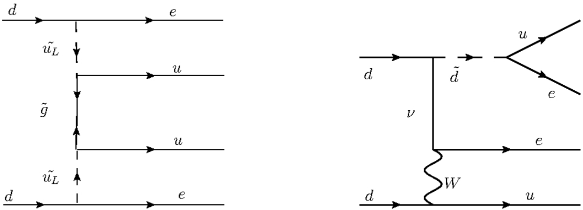
Left panel corresponds to $Y = 10^{-3}$ ($m_D = 0.174$ GeV); Right panel corresponds to $Y = 10^{-4}$ ($m_D = 0.0174$ GeV)



The allowed parameter regions (colored areas) which satisfy the constraints of different neutrino experimental constraints. Red, green, blue, orange and purple areas stand for $Y = 10^{-2}$, 10^{-3}, 10^{-4}, 10^{-5} and 3×10^{-6} respectively. The green lines correspond to the ratio of $r \equiv |A_{\rm heavy}/A_{\rm light}| = 1$ (solid), 10 (dashed) and 1000 (dot-dashed).

Appendix

RPV can induce $(\beta\beta)_{0\nu}$-decay in two different ways.



The short-range (left) and long-range (right) R-parity violating contribution to $(\beta\beta)_{0\nu}$-decay

Appendix

$$\eta_\lambda \simeq \frac{\pi\alpha_s}{6}\frac{\lambda'^2_{111}}{G_F^2 m^4_{\tilde{d}_R}}\frac{m_{\mathrm{p}}}{m_{\tilde{g}}}\cdot[1+(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}})^2]^2,$$

$$\eta_q = \sum_k \frac{\lambda'_{11k}\lambda'_{1k1}}{2\sqrt{2}G_F}[\sin 2\theta^d_{(k)}(\frac{1}{m^2_{\tilde{d}_1(k)}} - \frac{1}{m^2_{\tilde{d}_2(k)}})].$$

$$M^q_{ii'} = \frac{3}{16\pi^2}\lambda'_{ijk}\lambda'_{i'jk}[\sin(2\theta^k)m_{q^j}$$
$$\times(\frac{\log(x_2^{jk})}{x_2^{jk}-1} + \frac{(x_2^{jk}-1)\log(x_1^{jk})}{x_1^{jk}-1(x_2^{jk}-1)}) + (j\leftrightarrow k)],$$

where $\sin(2\theta^k) = 2m_{q^k}(A_k+\mu\tan\beta)\times[(m^2_{\tilde{q}^k_L} - m^2_{\tilde{q}^k_R} - 0.34M_Z^2\cos(2\beta))^2 -$

$$4(m_q^k(A_k+\mu\tan\beta))^2]^{-1/2},$$

$$x_1^{jk} = m^2_{q^j}/m^2_{\tilde{q}^k_1}, \quad x_2^{jk} = m^2_{q^j}/m^2_{\tilde{q}^k_2}.$$

Appendix

Therefore under our assumption, $m_{\beta\beta}$, which will be measured by the future experiments is not simply the active neutrino mass mixing.

Previously $m_{\beta\beta}$ was expected to $= < m_\nu > \equiv \sum_k^{\text{light}} (U_{ek})^2 m_k$ of light neutrino. Uncer the cancellation assumption, it should be corrected as

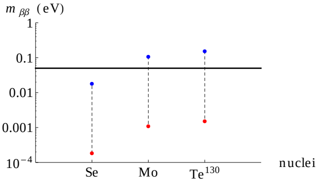
$$
\begin{aligned}
|< m_{\beta\beta} >_i| &= \left| \frac{me}{M_{\nu,i}} (\eta_\nu M_{\nu,i} - \eta_\nu \times \frac{M_{\nu,Ge}}{M_{N,Ge}} M_{N,i}) \right|, \\
&= \left| < m_\nu > \times (1 - \frac{M_{\nu,Ge} \cdot M_{N,i}}{M_{N,Ge} \cdot M_{\nu,i}}) \right| .
\end{aligned}
$$

We assume that $0.01 \text{ eV} < | < m_\nu > | < 1 \text{ eV}$
(for smaller than 0.01 eV, the effective would not be observed even without cancellation effect.)

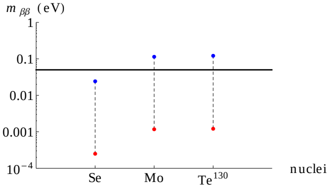
Appendix

Expected measured values of $\mid m_{\beta\beta} \mid_i$ in the future experiments under different destructive interferences.

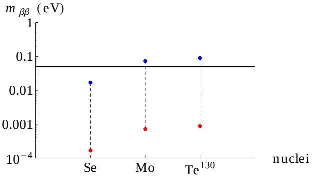
heavy neutrino mechanism,



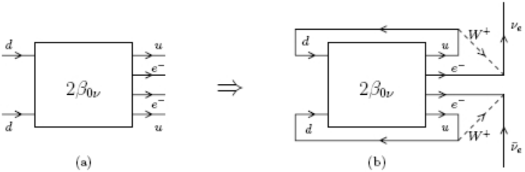
short range RPV,



long range RPV,



Appendix



L.H.S. : A Black-box diagram of the $(\beta\beta)_{0\nu}$-decay: 2d $\rightarrow$ 2u + 2e$^-$.

R.H.S. : If $(\beta\beta)_{0\nu}$-decay exists, then a $\bar{\nu}_e \rightarrow \nu_e$ transition can be generated through a $(\beta\beta)_{0\nu}$-decay Black-box, as this diagram shown. This diagram will give a nonzero Majorana mass term and prove that ν is Majorana particle.