The Majorana nature of massive neutrinos as a possible hint for new physics

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Outline of the talk

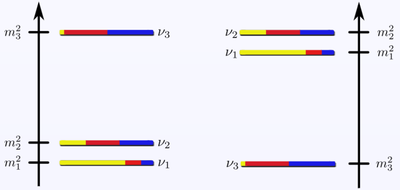
- The Majorana nature
- Pseudo-Dirac Scenarios and $\beta\beta0\nu$-decay
- Sterile neutrinos and $\beta\beta0\nu$-decay
- Multiple Mechanisms in the $\beta\beta0\nu$ Decay
- Conclusions

Global fit analysis of neutrino oscillation data
F. Capozzi, G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo 1312.2878 (2013).

Parameter	Best fit	1σ range
$\delta m^2/10^{-5}\ \mathrm{eV}^2$ (NH or IH)	7.54	7.32 – 7.80
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$ (NH)	2.44	2.38 – 2.52
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$ (IH)	2.40	2.33 – 2.47
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 $\oplus$ 5.31 – 6.10
δ/π (NH)	1.39	1.12 – 1.72
δ/π (IH)	1.35	0.96 – 1.59

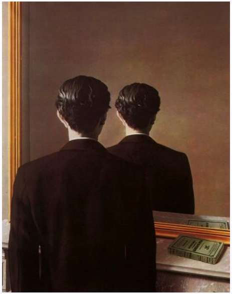
Open Questions in Neutrino Physics

- **Majorana or Dirac?**
- Absolute values of neutrino masses
- Hierarchy (normal $m_1 < m_2 < m_3$ or inverted $m_3 < m_1 < m_2$)
- CP-phases: δ, α_{31} and α_{21}



Majorana nature $\rightarrow \beta\beta0\nu$: $\quad (A, Z) \rightarrow (A, Z+2) + 2e^-$

- Process forbidden in the SM
- Lepton number is not conserved $\Delta L = \pm 2$
- Possible **if neutrinos are Majorana type**



René Magritte, *Portrait of Edward James*.

$\beta\beta0\nu$ experiments:

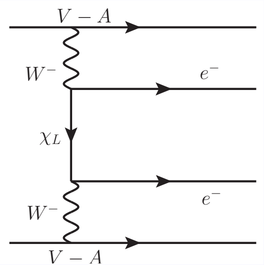
Important bounds already obtained by IGEX (^{76}Ge), CUORICINO (^{130}Te), NEMO3 (^{100}Mo) and H-Moscow experiment (^{76}Ge); **future experiments with sensitivity of** $|<m>| \sim (0.01 - 0.05)$ **eV**: GERDA (^{76}Ge), CUORE (^{130}Te), **EXO** (^{136}Xe), KamLAND-Zen (^{136}Xe), SNO+ (^{150}*Nd*), and many others...

T(^{76}Ge) $> 3.0 \times 10^{25}$ yr at 90% C.L.
[GERDA+HdM+IGEX] ArXiv 1307.4720

The standard mechanism: Light Majorana neutrino exchange

$\beta\beta 0\nu$-Decay contribution comes from the standard $\mathcal{L}^{CC}(V-A)$ weak interaction

$$\boxed{Tr[(\bar{e}_L\gamma_\alpha\nu_{eL})(\bar{e}_L\gamma_\beta\nu_{eL})] \propto \sum_k \xi_k m_k (U_{ek})^2}$$



- One can define a LNV parameter $\eta_\nu = \frac{<m>}{m_e}$

$$<m> = \left| \sum_j^{light} \left(U_{ej}^{PMNS}\right)^2 m_j \right| \ , \ (\text{all } light\ m_j \geq 0) \ ,$$

- U is **CP-violating**, in general:

$$(U_{ej})^2 = |Uej|^2 e^{i\alpha_j}, \quad j = 1, 2, 3$$

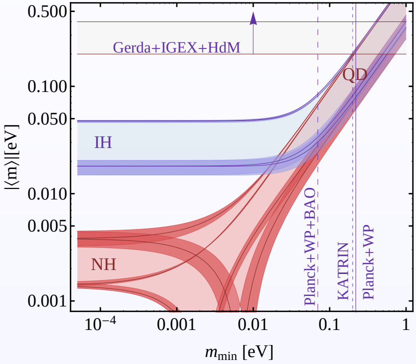
α_{21}, α_{31} - **Majorana CPV phases**.

- the leptonic chiral structure is S+ PS:

$$\mathcal{M} \propto <m>[\bar{e}(1+\gamma_5)e^c]A_{\alpha\beta}^{h.current}$$

Standard $\beta\beta0\nu$-decay amplitude is function of the effective Majorana mass parameter

$$|<m>| \;=\left|\sum_{j}^{light}(U_{ej}^{PMNS})^2 m_j\right|, \qquad m_j < 1eV$$



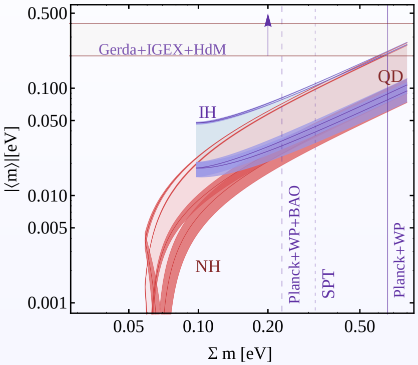
Plots obtained using 2σ uncertainty in the oscillation parameters

- ν Majorana nature
- If $|<m>| \lesssim$ few 10^{-2} $\rightarrow$ type of spectrum
- absolute scale of ν masses $\leftrightarrow$ lightest ν mass;
- with other sources data unique information on the **Majorana CP-violation phases** α_1 and α_2.

From the recent Planck data:

$$\Sigma\, m_i < 0.66\,\mathrm{eV}\ \text{at}\ 95\%\ \mathrm{C.L.}\ (\mathrm{Planck} + \mathrm{WP})$$

$$\Sigma\, m_i < 0.23\,\mathrm{eV}\ \text{at}\ 95\%\ \mathrm{C.L.}\ (\mathrm{Planck} + \mathrm{WP} + \mathrm{BAO})$$

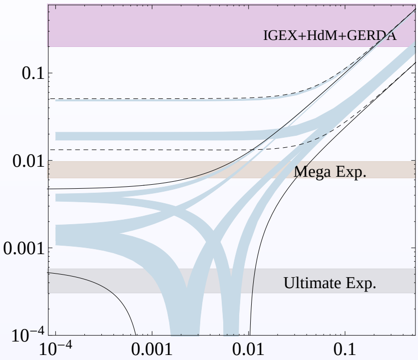


Plots obtained using 2σ uncertainty in the oscillation parameters

- Planck: assuming 3 species of degenerate massive neutrinos and a ΛCDM model
- EUCLID $\to \sim 0.01$ eV level of precision on the sum of the neutrino masses

Planck 2013 results. XVI. 1303.5076

$|\langle m \rangle|$ scales like $\sqrt{T^{0\nu}_{1/2}}$



- *mega*-experiments for $T^{0\nu}_{1/2} \sim 10^{27}$ yrs
- *ultimate*-experiments for $T^{0\nu}_{1/2} \sim 10^{29}$ yrs

Vissani et al.

$\beta\beta0\nu$-decay predictions can be modified?

Which are the other possible testable scenarios in the next generations of $\beta\beta0\nu$-decay experiments?

- In the 3 Majorana neutrino framework the $\beta\beta0\nu$-decay amplitude can well be zero in the NH case due to internal cancellations operated by the two Majorana phases and by uncertainty in the oscilaltion parameters. This behavior is not present in the IH case
  Bilenky + Pascoli + Petcov (2001), Hirsch (2011), ...
- What if some of the light active neutrinos are Dirac particles? In this case infact It does not participate in the amplitude of the $\beta\beta0\nu$-decay! (it is not possible to Wick-contract the neutrino field operator in order to obtain a neutrino propagator).
  Valle + Many authors about pseudo-Dirac neutrinos ...
- What if an extra sterile neutrino with 1eV-mass exists ? In the simplest 3+1 scheme the predictions for $|<m>|$ can be deeply modified
  Barry + Rodejohann + Zhang (2011), Girardi + AM + Petcov (2013), Li (2011)

I will show some examples based on
Girardi + AM + Petcov (2013)
AM + Peinado (2014)

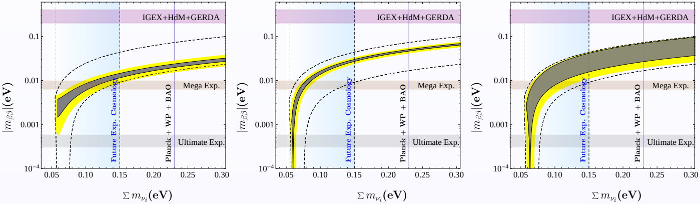
1) Pseudo-Dirac νs

The case of ONE Pseudo-Dirac neutrinos

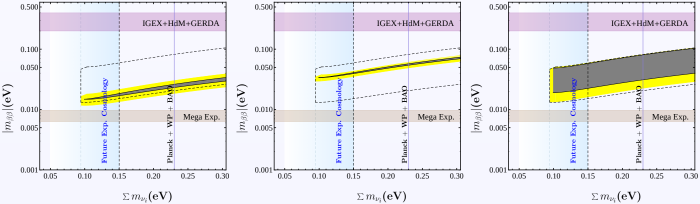
Particular attention to the case of NH (where can have cancellation in the ususal 3ν scenario)

$$|\langle m \rangle| = \left| m_1 \, |U_{e1}|^2 + m_2 \, |U_{e2}|^2 \, e^{i\lambda_{21}} + m_3 |U_{e3}|^2 e^{i\lambda_{31}} \right| .$$

NH



IH

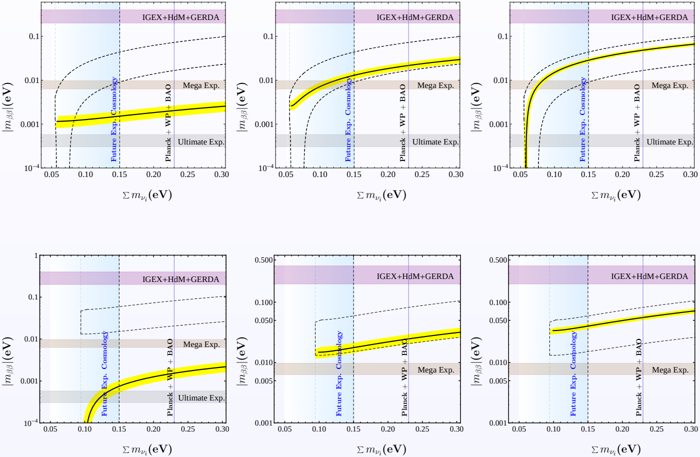


Particular attention to the case of NH (where can have cancellation in the ususal 3ν scenario)

$$|<m>| = \left| m_1 \, |U_{e1}|^2 + m_2 \, |U_{e2}|^2 \, e^{i\lambda_{21}} + m_3 |U_{e3}|^2 e^{i\lambda_{31}} \right| .$$

NH

IH

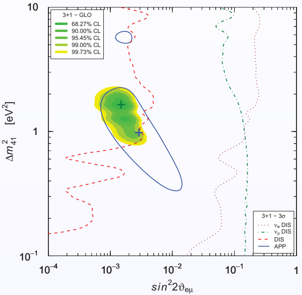


2) Sterile νs

$\beta\beta0\nu$-decay and sterile neutrinos: 3+1 scheme

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \delta_{\alpha\beta} - 4|U_{\alpha 4}|^2 \left(\delta_{\alpha\beta} - |U_{\beta 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), \qquad \sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance



Giunti, Levader, Li, Long 2013

	$\sin^2 2\theta_{14}$	Δm^2_{41} eV
global ν_e disapp.	0.09	1.78
	$\sin\theta_{14}$	Δm^2_{41} eV
global data	0.15	0.93

Kopp et al. arXiv:1303.3011

1. The $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data searches LSND (3.8σ), MiniBooNE ($E_\nu > 475\,MeV$), KARMEN,NOMAD,ICARUS, OPERA, ...
2. The $\overset{(-)}{\nu}_e$ disappearance data: the so called Gallium anomalies: GALLEX and SAGE ($2.9\ \sigma$).
3. The $\overset{(-)}{\nu}_e$ disappearance exps (reactors re-evaluation of flux): Bugey-3, Bugey-4, Goessgen, Krasnoyarsk, Rovno, ILL, Chooz, Palo Verde
4. $\overset{(-)}{\nu}_\mu$ disappearance data by CDHSW, from analysis of atmospheric neutrino oscillation experiments, MINOS(NC) data, SciBooNE-MiniBooNE neutrino and antineutrino data.

The contribution of the additional light Majorana neutrinos ν_4 in $\beta\beta0\nu$-decay amplitude, can change drastically the predictions for $|{<}\,m\,{>}|$ obtained in the case of 3-flavour neutrino mixing scheme, $|{<}\,m\,{>}^{(3\nu)}|$

Majorana Nature as a hint of New Physics:
The case of $\beta\beta 0\nu$-decay and sterile neutrinos
(Bilenky, Barry, Goswami, Rodejohann, Pascoli, Petcov, Zang, ...)

The contribution of the additional light Majorana neutrinos ν_4 or $\nu_{4,5}$ to the neutrinoless double beta ($\beta\beta 0\nu$-) decay amplitude, and thus to the $\beta\beta 0\nu$-decay effective Majorana mass $|<m>|$ can change drastically the predictions for $|<m>|$ obtained in the reference 3-flavour neutrino mixing scheme, $|<m>^{(3\nu)}|$

- Depending on the sign of $\Delta m^2_{31(2)}$, which cannot be determined from the presently available neutrino oscillation data, two types of neutrino mass spectrum are possible:
  - The 3+1 Scheme:

$$U = O_{24} O_{23} O_{14} V_{13} V_{12} \ diag(1, e^{i\alpha/2}, e^{i\beta/2}, e^{i\gamma/2}),$$

  - The 3+2 Scheme:

$$U = V_{35} O_{34} V_{25} V_{24} O_{23} O_{15} O_{14} V_{13} V_{12} \ diag(1, e^{i\alpha/2}, e^{i\beta/2}, e^{i\gamma/2}, e^{i\eta/2}) \,,$$

  where O_{ij} and V_{ij} are real and complex rotations in the $i-j$ plane.

The 3+1 Scheme

	$\sin^2 2\theta_{14}$	Δm^2_{41} eV
SBL rates only	0.13	0.44
SBL incl. Bugey3 spectr.	0.10	1.75
SBL + Gallium	0.11	1.80
SBL + LBL	0.09	1.78
global ν_e disapp.	0.09	1.78
	$\sin\theta_{14}$	Δm^2_{41} eV
global data	0.15	0.93

Table: The best fit values of the oscillation parameters $\sin^2 2\theta_{14}$ and Δm^2_{41} obtained in the $3+1$ scheme in (Kopp at al. arXiv:1303.3011) using different data sets. The values in the last row are obtained from the global fit of all available data in arXiv:1303.3011.

The masses of all neutrinos of interest for the present study satisfy $m_j \ll 1$ MeV, $j = 1, 2, 3, 4$.

$$|\langle m \rangle|^{2} = |a + e^{i\alpha} b + e^{i\beta} c + e^{i\gamma} d|^{2}.$$

The zeros of the first derivatives of $|\langle m \rangle|^{2}$ with respect to the phases α, β and γ are given by the following system of three equations:

$$\begin{aligned}
-2b[a\sin(\alpha) + c\sin(\alpha-\beta) + d\sin(\alpha-\gamma)] &= 0, \\
-2c[a\sin(\beta) - b\sin(\alpha-\beta) + d\sin(\beta-\gamma)] &= 0, \\
2d[-a\sin(\gamma) + b\sin(\alpha-\gamma) + c\sin(\beta-\gamma)] &= 0.
\end{aligned}$$

In order to solve this system we use the following parametrization:

$$\sin\alpha = \frac{2v}{1+v^2}, \qquad \sin\beta = \frac{2t}{1+t^2}, \qquad \sin\gamma = \frac{2u}{1+u^2}$$

where, respectively, $v \equiv \tan(\alpha/2)$, $t \equiv \tan(\beta/2)$, $u \equiv \tan(\gamma/2)$ with $\alpha, \beta, \gamma \neq \pi + 2k\pi$. In terms of the new variables the system in eq.(1) can be written as:

$$-\frac{2b}{1+v^2}\left[2av - \frac{2ct\left(1-v^2\right)}{t^2+1} + \frac{2c\left(1-t^2\right)v}{t^2+1} - \frac{2du\left(1-v^2\right)}{u^2+1} + \frac{2d\left(1-u^2\right)v}{u^2+1}\right] = 0,$$

$$\ldots$$

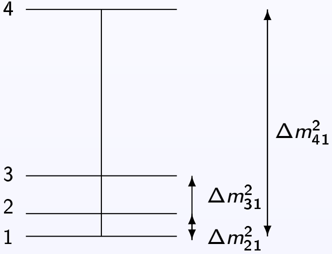
Girardi, AM, Petcov 2013

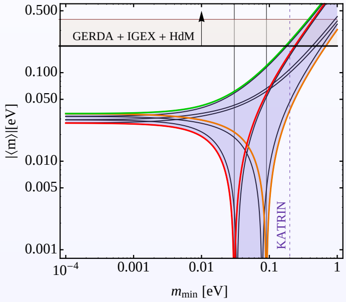
The case of 3+1 Scheme with NO Neutrino Mass Spectrum

$$|\!<m>\!| \;= |m_1 c_{12}^2 c_{13}^2 c_{14}^2 + m_2 e^{i\alpha} c_{13}^2 c_{14}^2 s_{12}^2 + m_3 e^{i\beta} c_{14}^2 s_{13}^2 + m_4 e^{i\gamma} s_{14}^2|\,,$$

The masses $m_{2,3,4}$ can be expressed in terms of the lightest neutrino mass m_1 and the three neutrino mass squared differences $\Delta m_{21}^2 > 0$, $\Delta m_{31}^2 > 0$ and $\Delta m_{41}^2 > 0$:

$$m_1 \equiv m_{min}, \quad m_2 = \sqrt{m_{min}^2 + \Delta m_{21}^2}, \qquad m_3 = \sqrt{m_{min}^2 + \Delta m_{31}^2} \;\text{ and }\; m_4 = \sqrt{m_{min}^2 + \Delta m_{41}^2}\,.$$

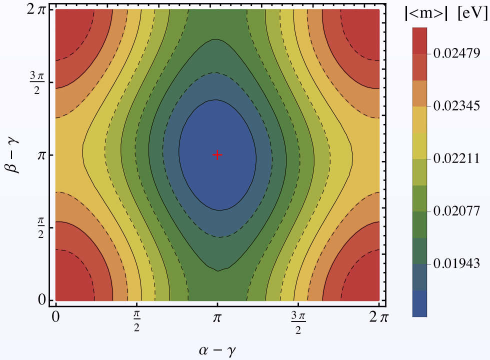




$$|<m>| \; = |\sqrt{\Delta m^2_{21}} e^{i\alpha} c^2_{13} c^2_{14} s^2_{12} + \sqrt{\Delta m^2_{31}} e^{i\beta} c^2_{14} s^2_{13} + \sqrt{\Delta m^2_{41}} e^{i\gamma} s^2_{14}| \, ,$$

For $m_1 = 0$ and any values of the CPV phases $(\alpha - \gamma, \beta - \gamma)$ we have:

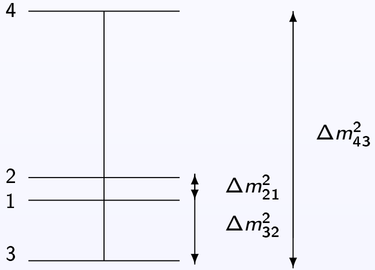
- $|<m>| \; \geq 0.018\, eV$ if $\Delta m^2_{41} = 0.93 \text{ eV}^2$;
- $|<m>| \; \geq 0.027\, eV$ for $\Delta m^2_{41} = 1.78 \text{ eV}^2$. If instead of $\sin^2\theta_{14} = 0.0223$ we use $\sin^2\theta_{14} = 0.017$ (0.047), we get $|<m>| \; \geq 0.019$ (0.059) eV.

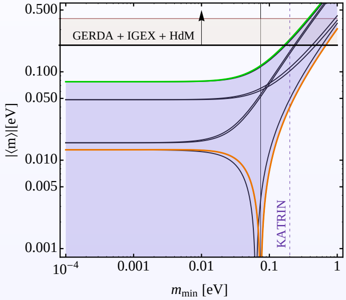


$$|<m>| = |m_1 c_{12}^2 c_{13}^2 c_{14}^2 + m_2 e^{i\alpha} c_{13}^2 c_{14}^2 s_{12}^2 + m_3 e^{i\beta} c_{14}^2 s_{13}^2 + m_4 e^{i\gamma} s_{14}^2|\,.$$

The masses $m_{1,2,4}$ can be expressed in terms of the lightest neutrino mass $m_{min} = m_3$ and the neutrino mass squared differences as follows:

$$\begin{aligned} m_1 &= \sqrt{m_{min}^2 + |\Delta m_{32}^2| - \Delta m_{21}^2}, \quad m_2 = \sqrt{m_{min}^2 + |\Delta m_{32}^2|}, \quad m_4 = \sqrt{m_{min}^2 + \Delta m_{43}^2}\,, \\ m_3 &= m_{min}\,, \quad \Delta m_{21}^2 > 0\,, \quad \Delta m_{32}^2 < 0\,, \quad \Delta m_{43}^2 > 0\,. \end{aligned} \tag{1}$$



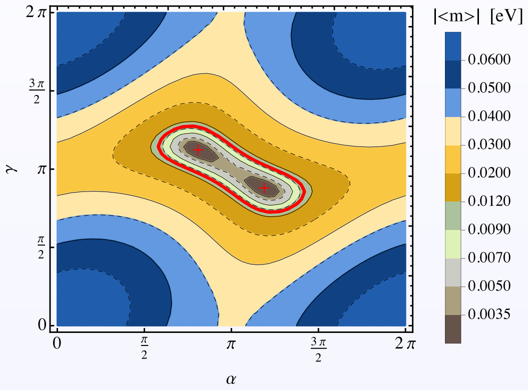


The Case of $m_3 = 0$

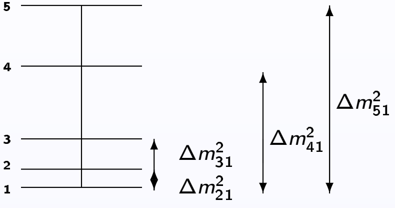
The effective Majorana mass in this case is

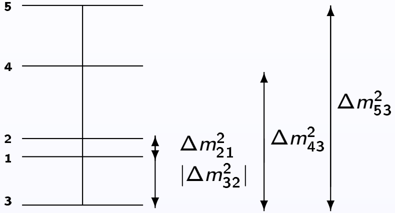
$$|<m>| \;=\left|\sqrt{|\Delta m^2_{32}| - \Delta m^2_{21}}\,(c_{12}c_{13}c_{14})^2 + \sqrt{|\Delta m^2_{32}|}\,(c_{13}c_{14}s_{12})^2 e^{i\alpha} + \sqrt{\Delta m^2_{43}}\,s^2_{14}e^{i\gamma}\right|. \quad (2)$$

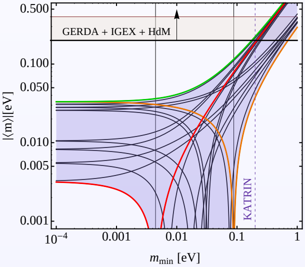
Now only two phases enter into the expression of $|<m>|$: α and γ.
Both minima correspond to $|<m>| \;= 0$ independently of the value of Δm^2_{43}. However, the location of the minima on the $\alpha - \gamma$ plane depends on Δm^2_{43}.

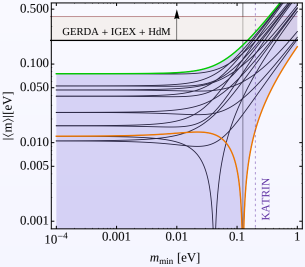


$$|<m>| = |m_1 c_{12}^2 c_{13}^2 c_{14}^2 c_{15}^2 + m_2 e^{i\alpha} c_{13}^2 c_{14}^2 c_{15}^2 s_{12}^2 + m_3 e^{i\beta} c_{14}^2 c_{15}^2 s_{13}^2 + m_4 e^{i\gamma} c_{15}^2 s_{14}^2 + m_5 e^{i\eta} s_{15}^2|$$







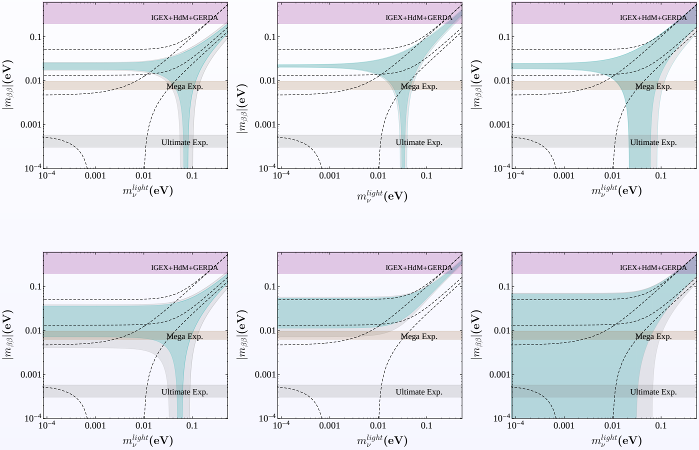


The case of ONE Pseudo-Dirac light neutrinos

Consider the scenario with one Pseudo-Dirac neutrino + one sterile extra neutrino

NH

IH

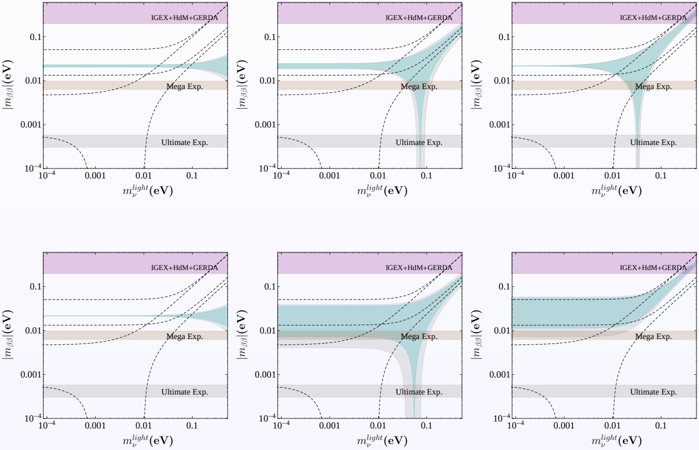


The case of TWO Pseudo-Dirac light neutrinos

Consider the scenario with one Pseudo-Dirac neutrino + one sterile extra neutrino

NH

IH



3) $\Delta L = \pm 2$

If $\beta\beta0\nu$ decay will be **observed**, the question will inevitably arise:

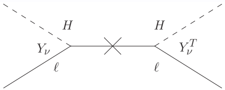
Which mechanism is triggering the decay?
How many mechanisms are involved?

$$\boxed{[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(E,Z)|\sum_i \eta_i^{LNV} M_i^{0\nu}|^2}$$

- $\eta_i^{LNV} \iff$ mechanism type i
- η_i^{LNV} can be real or complex.
- $G^{0\nu}(E,Z)$ is the phase space factor
- $M_i^{0\nu}$ is the nuclear matrix element (NME)
- These mechanisms might trigger $\beta\beta0\nu$-decay **individually or together** and can **interfere or not**.

$\beta\beta0\nu$ **decay is allowed by a wide range of models**: from the standard mechanism of light Majorana neutrino exchange, Left-Right Symmetry or R-parity violating Supersymmetry (SUSY)...

3 RH $N_R \sim (1,0)$ N_k with masses $M_k \gtrsim 10$ GeV i.e. $M_k \gg 100$ MeV (typical energy scale of the $\beta\beta0\nu$-decay)



$$\mathcal{L}_{Y+M} = -(Y_\nu)_{jl}(\bar{\ell}_L \tilde{H})_j N_{lR} - \frac{1}{2}\overline{(N_{lR})^c}(M^N)_{ll'} N_{l'R} + h.c.$$

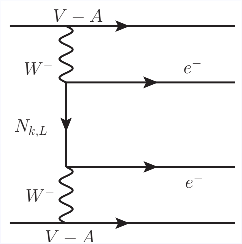


Figure: *

$\eta_N^L[\bar{e}(1+\gamma_5)e^c]$

V-A coupling: The LNV parameter is:

$$\boxed{\eta_N^L = \sum_k^{heavy} U_{ek}^2 \frac{m_p}{M_k},}$$

m_p= proton mass,
U_{ek} is the mixing matrix due to $V-A$ coupling.

RH Heavy Majorana neutrino exchange with $M_k \gtrsim 10$ GeV

$SU(2)_L \otimes SU(2)_R$

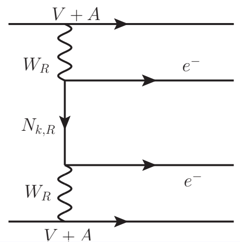


Figure: *

$\eta_N^R[\bar{e}(1-\gamma_5)e^c]$

V+A coupling in the CC current

$$\mathcal{L}_{weak} \supset (\bar{e}\gamma_\alpha(1+\gamma_5)\nu_{eR})W^-_{\mu R}$$

where $\nu_{eR} = \sum_k V_{ek} N_{kR},\ C\bar{N}_k^T = \xi N_k.$

The LNV parameter is:

$$\boxed{\eta_N^R = \left(\frac{M_W}{M_{WR}}\right)^4 \sum_k^{heavy} V_{ek}^2 \frac{m_p}{M_k}.}$$

$$M_{W_R} \gtrsim 2.5\,TeV.$$

Here V_{ek} is the mixing matrix by which N_k couple to the electron in the $(V+A)$ charged lepton current.

The LNV λ'-couplings is given by in the **R-parity breaking part of the superpotential**:

$$\mathcal{L}_{R\!\!\!/_p} = \lambda'_{111}\left[(\bar{u}_L\ \bar{d}_L)\begin{pmatrix} e^c_R \\ -\nu^c_{eR}\end{pmatrix}\tilde{d}_R + (\bar{e}_L\ \bar{\nu}_{eL})d_R\begin{pmatrix}\tilde{u}^*_L \\ -\tilde{d}^*_L\end{pmatrix} + (\bar{u}_L\ \bar{d}_L)d_R\begin{pmatrix}\tilde{e}^*_L \\ -\tilde{\nu}^*_{eL}\end{pmatrix} + h.c.\right]$$

Assuming the **dominance of the gluino exchange** the LNV parameter is:

$$\boxed{\eta_{\lambda'} \sim \frac{\pi\alpha_s}{m_{\tilde{g}}}\frac{\lambda'^2_{111}}{m^4_{\tilde{f}}}, \quad \alpha_s = \frac{g_3^2}{4\pi}}$$

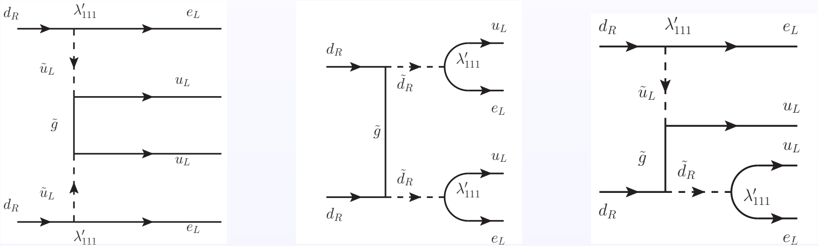


Figure: *

Hirsch, K.-Kleingrothaus, Kovalenko Phys. Rev. Lett.75 (1995)

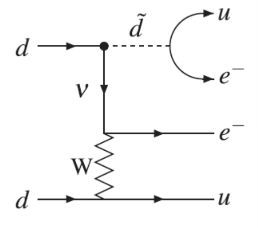


Figure: *

Faessler, Gutsche, Kovalenko, Simkovic Phys.Rev. D 77 (2008)

- The mixing between the scalar superpartners $\tilde{q}_{L,R}$ of the left and right handed quarks $q_{L,R}$ plays a crucial role.
- The squark-gluino mechanisms is due to the non-diagonality of the squark mass matrix.
- $\tilde{q}_L$ and $\tilde{q}_R$ are superpositions of mass eigenstates with a given mxing angle $\theta^d_{(k)}$

$$\boxed{\eta_{\tilde{q}} \sim \sum_k \frac{\lambda'_{11k}\lambda'_{1k1}}{G_F m_{\tilde{d}_{(k)}}} \sin(2\theta^d_{(k)})}$$

$\eta_{\tilde{q}} \neq 0$ if m_i of light neutrinos is zero but it is zero if $\theta^d_{(k)} = 0$

Multiple Mechanisms: The Analysis

- Case of two Non Interfering Machanisms

$$[T^{0\nu}_{1/2,i} G^{0\nu}_i(E,Z)]^{-1} = |\eta_\nu|^2 ({M'}^{0\nu}_{i,\nu})^2 + |\eta_N|^2 ({M'}^{0\nu}_{i,N})^2|$$

- Case of two Interfering Mechanisms

$$[T^{0\nu}_{1/2,i} G^{0\nu}_i(E,Z)]^{-1} = |\eta_\nu|^2 ({M'}^{0\nu}_{i,\nu})^2 + |\eta_{\lambda'}|^2 ({M'}^{0\nu}_{i,\lambda'})^2 + 2\cos\alpha {M'}^{0\nu}_{i,\lambda'} {M'}^{0\nu}_{i,\nu} |\eta_\nu||\eta_{\lambda'}|$$

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(E,Z)|\sum_i \eta_i^{LNV} M_i^{0\nu}|^2$$

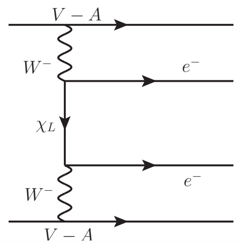


Figure: *

amplitude $\propto$
$\eta_\nu[\bar{e}(1+\gamma_5)e^c]$

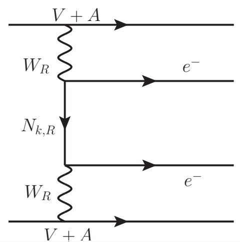


Figure: *

amplitude $\propto$
$\eta_N^R[\bar{e}(1-\gamma_5)e^c]$

light LH and heavy RH Majorana neutrino exchanges $\rightarrow |\eta_\nu|$ and $|\eta_R|$

$$\begin{cases} \dfrac{1}{T_1 G_1} = |\eta_\nu|^2 |M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{1,N}|^2, \\ \dfrac{1}{T_2 G_2} = |\eta_\nu|^2 |M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{2,N}|^2 \end{cases}$$

$|\eta_\nu|^2, |\eta_R|^2 < 0$ are unphysical. Positive solutions for $|\eta_\nu|^2$ and $|\eta_R|^2$ ($A_1 < A_2$) if:

$$\frac{T_1 G_1 |M'^{0\nu}_{1,N}|^2}{G_2 |M'^{0\nu}_{2,N}|^2} \leq T_2 \leq \frac{T_1 G_1 |M'^{0\nu}_{1,\nu}|^2}{G_2 |M'^{0\nu}_{2,\nu}|^2},$$

If one of the two solutions is zero then **only one mechanism is active.**
Using the values "CD-Bonn, large, $g_A = 1.25$", we get the positivity conditions:

$$0.15 \leq \frac{T^{0\nu}_{1/2}(^{100}Mo)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.18 \qquad , 0.17 \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.22$$

Very narrow intervals!

Constrains on $\beta\beta 0\nu$ LNV parameters

$\beta\beta 0\nu$ **Decay Experiments: Constraints on isotopes half-lives:**

- $T^{0\nu}_{1/2}(^{76}Ge) = 2.23^{+0.44}_{-0.31} \times 10^{25} y$ H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, Mod. Phys. Lett. A **21** (2006) 1547
- $T^{0\nu}_{1/2}(^{76}Ge) \geq 1.9 \times 10^{25} y$ Heidelberg-Moscow, Eur.Phys.J. A12 (2001) 147-154
- $T^{0\nu}_{1/2}(^{100}Mo) \geq 5.8 \times 10^{23} y$ [NEMO], arXiv:0807.2336 [nucl-ex].
- $T^{0\nu}_{1/2}(^{130}Te) \geq 3.0 \times 10^{24} y$ [CUORICINO], Phys. Rev. C **78**, 035502 (2008).
- $T^{0\nu}_{1/2}(^{136}Xe) \geq 1.6 \times 10^{25} y$ [EXO-200] ArXiv 1205.5608
- T(^{76}Ge) $> 2.1 \times 10^{25}\mathrm{yr\ at\ 90\%\ C.L.}$ [GERDA]
- T(^{76}Ge) $> 3.0 \times 10^{25}\mathrm{yr\ at\ 90\%\ C.L.}$ [GERDA+HdM+IGEX] ArXiv 1307.4720

From **Tritium** β **decay**:

- Troitzk and Mainz experiments $\Rightarrow |{<}m{>}| \; < 2.3$ eV at 95% C.L.
- **KATRIN** experiment $\Leftrightarrow$ sensitivity of $|{<}m{>}| \; \simeq 0.20$ eV, $\Rightarrow$ it will probe the region of the QD spectrum.

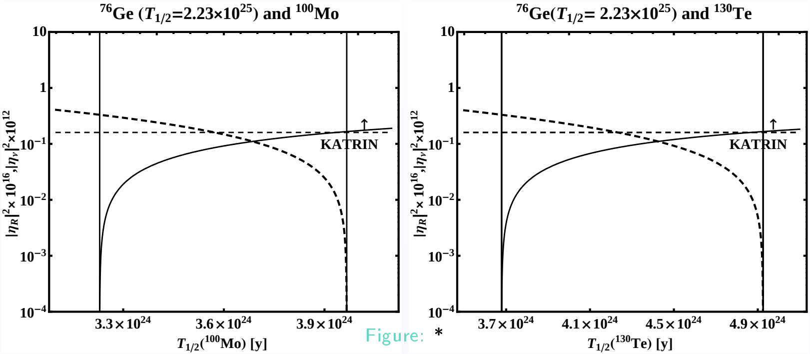


Figure: *

The values of the rescaled parameters $|\eta_\nu|^2$ (solid line) and $|\eta_R|^2$ (dashed lined), for $T^{0\nu}_{1/2}(^{76}Ge)$ and i) $T^{0\nu}_{1/2}(^{100}Mo)$ and ii) $T^{0\nu}_{1/2}(^{100}Te)$ lying in a specific interval. The physical (positive) solutions are delimited by the two vertical lines. The horizontal dashed line corresponds to the prospective upper limit from the upcoming ^3H β-decay experiment KATRIN.

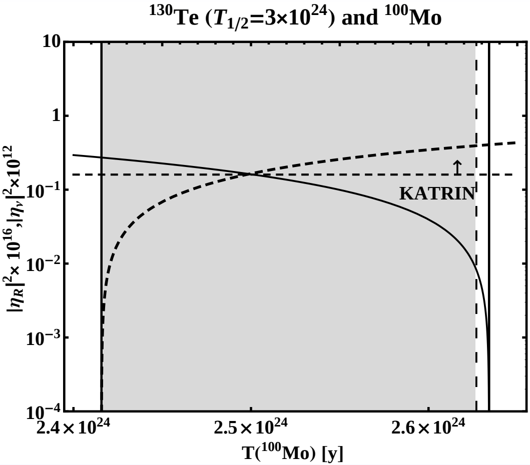
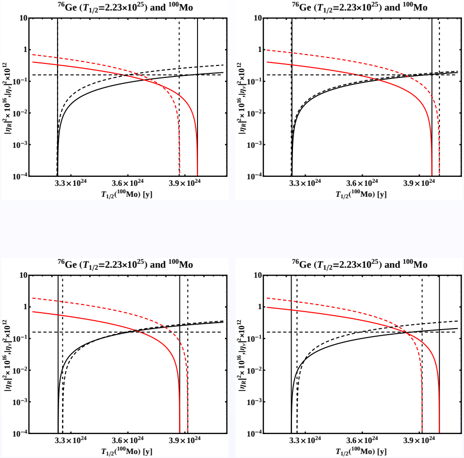


Figure: *

The values of the rescaled parameters $|\eta_\nu|^2$ (solid line) and $|\eta_R|^2$ (dashed lined). The physical (positive) solutions are delimited by the two vertical lines. The gray region is an excluded due to the lower bound on $T^{0\nu}_{1/2}(^{76}Ge)$.

Results: change smaller than 10%



i) CD-Bonn potential, $g_A = 1.25$ (solid lines) and $g_A = 1$ (dashed lines) (upper left panel); ii) CD-Bonn (solid lines) and Argonne (dashed lines) potentials with $g_A = 1.25$ (upper right panel); iii) CD-Bonn (solid lines) and Argonne (dashed lines) potentials with $g_A = 1.0$ (lower left panel); iv) Argonne potential with $g_A = 1.25$ (solid lines) and $g_A = 1$ (dashed lines) (lower right panel).

Comments

- If the $T^{0\nu}_{1/2}$ of one of the three nuclei ^{76}Ge, ^{100}Mo or ^{130}Te will be observed, the positivity condition, i.e. $|\eta_k^{LNV}| \geqslant 0$, constrains the other two to lie in specific intervals, determined by the measured half-life and the relevant NMEs and phase-space factors. This feature is common to all cases of two non-interfering mechanisms generating the $\beta\beta 0\nu$-decay.

- The indicated specific half-life intervals for the various isotopes, are **stable** with respect to the change of the NMEs (Argonne or CD- Bonn Potentials and $g_A = 1, 1.25$).
- The intervals of $T2/T1$ depend on the type of the two non-interfering mechanisms. However, the differences in the cases of the exchange of heavy Majorana neutrinos coupled to (V+A) currents and i) light Majorana neutrino exchange, or ii) the gluino exchange mechanism, are extremely small for the isotopes considered.

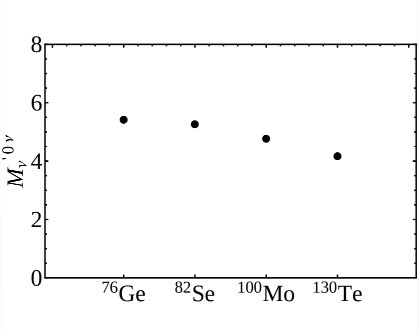
- **if it will be possible to rule out one of these mechanisms as the cause of $\beta\beta 0\nu$decay, most likely one will be able to rule out all three of them (the NMEs are too similar).**

Important feature of the **NMEs** considered within the the Self-consistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA) Method: they **differ relatively little!**:

$$|M_{i\kappa} - M_{j\kappa}| \ll M_{i\kappa}, M_{j\kappa}$$

$$\frac{|M_{i\kappa} - M_{j,\kappa}|}{(0.5(M_{i\kappa} + M_{j,\kappa}))} \sim 10^{-2} - 10^{-3}$$

$$i \neq j =^{76} Ge,^{82} Se,^{100} Mo,^{130} Te$$



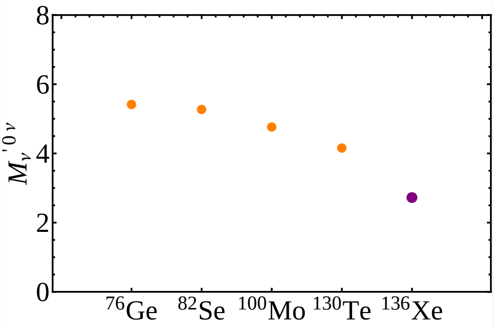
From Simkovic

EXO Collaboration ArXiv 1205.5608

$$\boxed{T^{0\nu}_{1/2}(^{136}Xe) \geq 1.6 \times 10^{25} y}$$

$$\frac{|M_{i\kappa} - M_{j,\kappa}|}{(0.5(M_{i\kappa} + M_{j,\kappa}))} \sim 10^{-1}$$

$$i =^{76} Ge, \quad j =^{136} Xe$$



Using the EXO Limit in the case of two non interfering mechanisms

Positive solutions only if:

$$\frac{T_1\, G_1 |M'^{0\nu}_{1,B}|^2}{G_2 |M'^{0\nu}_{2,B}|^2} \leq T_2 \leq \frac{T_1\, G_1 |M'^{0\nu}_{1,A}|^2}{G_2 |M'^{0\nu}_{2,A}|^2}\,,$$

The inequality can be enforced if e.g $T_1 > T_{min}$:

$$\boxed{T_2 \geq \frac{G_1}{G_2} \frac{|M'^{0\nu}_{1,B}|^2}{|M'^{0\nu}_{2,B}|^2}\, T_{min}}$$

For example: $T^{0\nu}_{1/2}(^{136}Xe) \equiv T_1 > 1.6 \times 10^{25}$yr and $T^{0\nu}_{1/2}(^{76}Ge) \equiv T_2$

we use standard ν and RH Heavy N exchange:

Argonne Potential g_A=1.25 (1.0) $T^{0\nu}_{1/2}(^{76}Ge) > 3.03\,(2.95)\,10^{25}\,yr$

Cd-Bonn Potential g_A=1.25 (1.0) $T^{0\nu}_{1/2}(^{76}Ge) > 2.08\,(1.9)\,10^{25}\,yr$

Using the EXO Limit in the case of two non interfering mechanisms

Light standard and RH heavy Neutrino

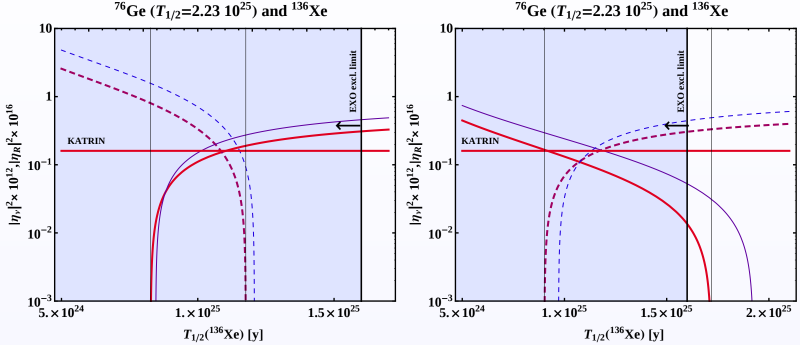


Figure: The values of the rescaled parameters $|\eta_\nu|^2$ (solid lines) and $|\eta_R|^2$ (dashed lines) using $T^{0\nu}_{1/2}(^{76}Ge)$ and $T^{0\nu}_{1/2}(^{136}Xe)$ and fixing $T^{0\nu}_{1/2}(^{76}Ge) = 2.23\times 10^{25}$. The solutions using Argonne (left panel) and Cd-Bonn (right panel) Potential are shown in the case of $g_A = 1.25$ (thick lines) and $g_A = 1$ (thin lines).

Possible discrimination of different couple of mechanisms

Using the Argonne Potential to determine the NMEs with $g_A = 1.25(1.0)$ one gets:

- standard light neutrino exchange and the heavy RH Majorana neutrino exchange:

$$1.90\,(1.85) \leq \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 2.70\,(2.64)$$

- heavy right-handed Majorana neutrino exchange and the gluino exchange:

$$2.70\,(2.64) \leq \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 2.78\,(2.67)$$

- squark-neutrino exchange mechanism and the RH Neutrino exchange:

$$2.52\,(2.40) \leq \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 2.70\,(2.64)$$

Possible discrimination of different couple of mechanisms

Using the Cd-Bonn Potential to determine the NMEs with $g_A = 1.25(1.0)$ one gets:

- standard light neutrino exchange and the heavy RH Majorana neutrino exchange:

$$1.30\,(1.16) \leq \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 2.47\,(2.30)$$

- heavy right-handed Majorana neutrino exchange and the gluino exchange:

$$1.30\,(1.16) \leq \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 4.43\,(4.25)$$

- squark-neutrino exchange mechanism and the RH Neutrino exchange:

$$1.30\,(1.16) \leq \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 2.95\,(2.81)$$

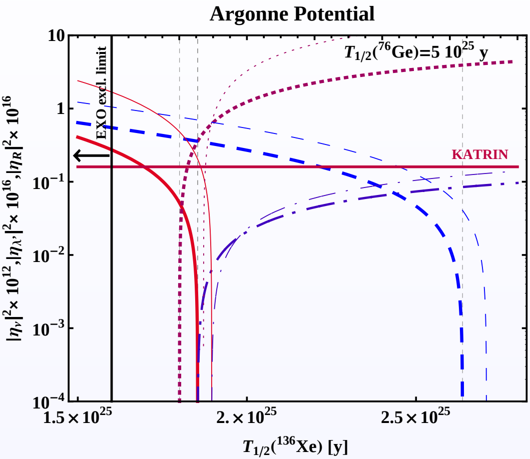


Figure: i) $|\eta_\nu|^2$ and $|\eta_R|^2$ (dot-dashed and dashed lines) and ii) $|\eta_{\lambda'}|^2$ and $|\eta_R|^2$ (solid and dotted lines) The curves are obtained using the sets of NMEs calculated using the Argonne potential.

Possible discrimination of different couple of mechanisms

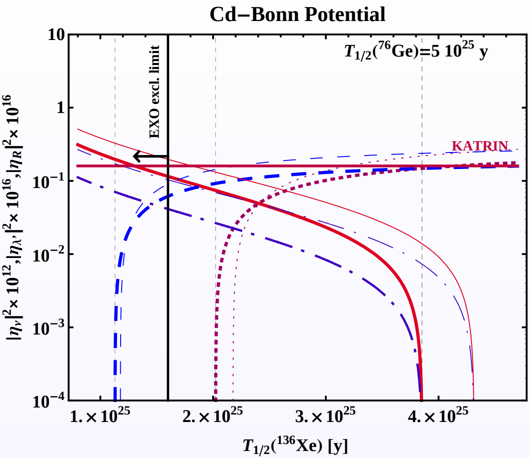


Figure: i) $|\eta_\nu|^2$ and $|\eta_R|^2$ (dot-dashed and dashed lines) and ii) $|\eta_{\lambda'}|^2$ and $|\eta_R|^2$ (solid and dotted lines) The curves are obtained using the sets of NMEs calculated using the Cd-Bonn potential.

Example: light Majorana neutrino and gluino exchange mechanisms

$$\boxed{[T^{0\nu}_{1/2,i} G^{0\nu}_i(E,Z)]^{-1} = |\eta_\nu|^2 (M'^{0\nu}_{i,\nu})^2 + |\eta_{\lambda'}|^2 (M'^{0\nu}_{i,\lambda'})^2 + 2\cos\alpha M'^{0\nu}_{i,\lambda'} M'^{0\nu}_{i,\nu} |\eta_\nu||\eta_{\lambda'}|\,.}$$

$$|\eta_\nu|^2 = \frac{D_1}{D}\,, \quad |\eta_{\lambda'}|^2 = \frac{D_2}{D}\,, \quad z \equiv 2\cos\alpha |\eta_\nu||\eta_{\lambda'}| = \frac{D_3}{D}\,,$$

$$D = \begin{vmatrix} (M'^{0\nu}_{1,\nu})^2 & (M'^{0\nu}_{1,\lambda'})^2 & M'^{0\nu}_{1,\lambda'} M'^{0\nu}_{1,\nu} \\ (M'^{0\nu}_{2,\nu})^2 & (M'^{0\nu}_{2,\lambda'})^2 & M'^{0\nu}_{2,\lambda'} M'^{0\nu}_{2,\nu} \\ (M'^{0\nu}_{3,\nu})^2 & (M'^{0\nu}_{3,\lambda'})^2 & M'^{0\nu}_{3,\lambda'} M'^{0\nu}_{3,\nu} \end{vmatrix}, D_1 = \begin{vmatrix} 1/T_1 G_1 & (M'^{0\nu}_{1,\lambda'})^2 & M'^{0\nu}_{1,\lambda'} M'^{0\nu}_{1,\nu} \\ 1/T_2 G_2 & (M'^{0\nu}_{2,\lambda'})^2 & M'^{0\nu}_{2,\lambda'} M'^{0\nu}_{2,\nu} \\ 1/T_3 G_3 & (M'^{0\nu}_{3,\lambda'})^2 & M'^{0\nu}_{3,\lambda'} M'^{0\nu}_{3,\nu} \end{vmatrix}$$

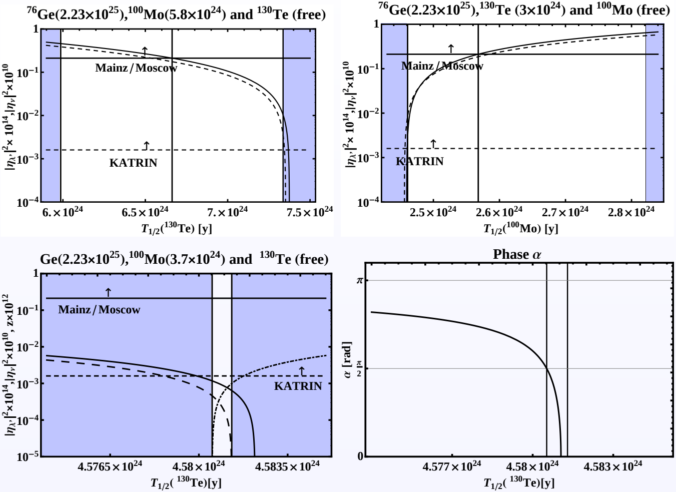
$$D_2 = \begin{vmatrix} (M'^{0\nu}_{1,\nu})^2 & 1/T_1 G_1 & M'^{0\nu}_{1,\lambda'} M'^{0\nu}_{1,\nu} \\ (M'^{0\nu}_{2,\nu})^2 & 1/T_2 G_2 & M'^{0\nu}_{2,\lambda'} M'^{0\nu}_{2,\nu} \\ (M'^{0\nu}_{3,\nu})^2 & 1/T_3 G_3 & M'^{0\nu}_{3,\lambda'} M'^{0\nu}_{3,\nu} \end{vmatrix}, \quad D_3 = \begin{vmatrix} (M'^{0\nu}_{1,\nu})^2 & (M'^{0\nu}_{1,\lambda'})^2 & 1/T_1 G_1 \\ (M'^{0\nu}_{2,\nu})^2 & (M'^{0\nu}_{2,\lambda'})^2 & 1/T_2 G_2 \\ (M'^{0\nu}_{3,\nu})^2 & (M'^{0\nu}_{3,\lambda'})^2 & 1/T_3 G_3 \end{vmatrix}.$$

Positivity conditions:

$$|\eta_\nu|^2 > 0 \quad |\eta_\lambda|^2 > 0$$

$$-2|\eta_\nu||\eta_{\lambda'}| \leq 2\cos\alpha |\eta_\nu||\eta_{\lambda'}| \leq 2|\eta_\nu||\eta_{\lambda'}|$$

Comment: in most of the cases analyzed destructive interference was found. $|\eta_\nu|^2 \times 10^{10}$ (thick line), $|\eta_{\lambda'}|^2 \times 10^{14}$ (dashed line) and $z = 2\cos\alpha|\eta_\nu||\eta_{\lambda'}| \times 10^{12}$ (dot-dashed line).



Conclusion(s)

- the Majorana nature of massive neutrino and thus $\beta\beta0\nu$decay can test the compatibility of data sets with the existence of extra sterile neutrino states and the general properties of the neutrino mass matrix.
- The contribution of the additional light Majorana neutrinos can change drastically the predictions for $|<m>|$ obtained in the reference 3- avour neutrino mixing scheme: NH and IH have different features.
- Significant experimental efforts have been made to unveil the possible Majorana nature of massive neutrinos by searching for neutrinoless double beta decay with increasing sensitivity (last year GERDA!).
- Cosmology will provide us important information to be combined with $\beta\beta0\nu$results: e.g. EUCLID combined with Planck results

STAY TUNED!

Conclusion(s)

- The nature - Dirac or Majorana - of massive neutrinos, can be possibly related to New Physics beyond that predicted by the Standard Model.
- If we will observe $\beta\beta0\nu$ decay we must understand which $\Delta L = 2$ mechanism(s) trigger the decay and if they interfere or not.
- All cases of **two non-interfering mechanisms** have the same features.
- If taking into account all relevant uncertainties, experimental data lie outside the interval of physical solutions $\Rightarrow$ $\beta\beta0\nu$ decay is not generated by the two mechanisms considered.
- The method considered can be generalised to the case of more than two $\beta\beta0\nu$-decay mechanisms.
- It allows to treat the cases of CP conserving and CP nonconserving couplings generating the $\beta\beta0\nu$-decay in a unique way.

Thank you