Neutrinoless Double Beta Decay and Heavy Sterile Neutrinos

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Rencontres de Moriond, La Thuile

Neutrinoless Double Beta Decay and Heavy Sterile Neutrinos;
Manimala Mitra, Goran Senjanović, Francesco Vissani; Nucl. Phys. B **856** (2012) 26

Plan of the talk:

- Neutrinoless double beta decay in Type-I seesaw scenario
- Type-I seesaw $\rightarrow$ the most basic seesaw scenario which generates Majorana mass of light neutrinos
- Discussion on heavy sterile neutrino contribution in $0\nu2\beta$; how they can saturate the bound
- Other seesaw extensions and neutrinoless double beta decay

Experimental Observation:

Massive but small non-zero neutrino masses m_i and mixing U from oscillation and non-oscillation experiments

- Cosmological bound on the sum of light neutrino masses

$$\sum_i m_i < 0.26 \text{ eV}$$

Putter et al, arXiv: 1201.1909[astro.ph, CO]

$$\Delta m^2_{21} = (6.99 - 8.18) \times 10^{-5}\,\mathrm{eV}^2$$
$$\Delta m^2_{31} = (2.06 - 2.67) \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{12} = 0.265 - 0.364$$
$$\sin^2\theta_{23} = 0.34 - 0.64$$
$$\sin^2\theta_{13} = 0.005 - 0.050$$

Fogli et al., PRD 84 (2011) 053007

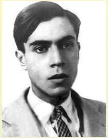
Also Schwetz et al., New.J.Phys. 13(2011) 109401

In standard model neutrinos are massless

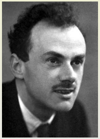
The above indicates extension of standard model

Contd

$\boxed{\text{Neutrino Mass}}$



$\Downarrow$



$\boxed{\text{Dirac or Majorana?}}$

- Dirac mass, $m_D \bar{\nu}_L N_R$ $\rightarrow$ lepton number is conserved
- Majorana mass, $m\nu^T C^{-1} \nu$ $\rightarrow$ lepton number is violated by two unit

Lepton number is a classical symmetry of standard model

Neutrinoless double beta decay: What and Why?

Neutrinoless double beta decay ($0\nu2\beta$)

The process is $(A, Z) \rightarrow (A, Z+2) + 2e^-$

Probing lepton number violation

- $T_{1/2}$ is the half-life of this process
- The Heidelberg-Moscow bound $\rightarrow T_{1/2} \geq 1.9 \times 10^{25} yrs$

H. V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. **A12**, 147-154 (2001)

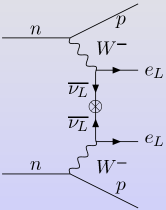
Is it due to light Majorana neutrinos?

If light neutrinos are Majorana, their mass violate lepton number by two units

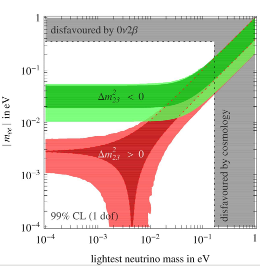
$$\boxed{0\nu2\beta \Longleftrightarrow \text{Majorana mass of light neutrinos?}}$$

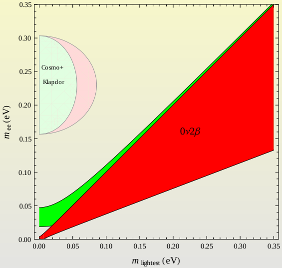
Any signature in neutrinoless double beta decay process is due to only light Majorana neutrinos?

The light neutrino contribution



m_{ee} is the effective mass of light neutrinos in $0\nu 2\beta$ process





Vissani 1999; Feruglio *et al.* 2002; Vissani, Strumia 2006;

- Experimental hint on neutrinoless double beta decay by Klapdor and collaborators; Klapdor-Kleingrothaus et al., PLB 586, 2004

Combining cosmological bound with Klapdor at 95% C.L, the effective mass of light neutrinos in neutrinoless double beta decay process is not compatible with cosmology+Klapdor result.

Light vs Heavy

The effective Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \xi_1 \frac{llHH}{M} + \xi_2 \frac{qqql}{M^2} + \xi_3 \frac{(q\bar{d}l)^2}{M^5} + \ldots$$

Weinberg, PRL 43, 1979

Historical analogy

$$\mathcal{L}_{eff} = \mathcal{L}_{QED} + \frac{g^2}{M_W^2} J_\mu^\dagger J^\mu + \ldots.$$

- $\xi_1 \frac{llHH}{M} \rightarrow$ d-5 operator. Generates neutrino mass
- $\xi_2 \frac{qqql}{M^2} \rightarrow$ d-6. Relevant for proton decay
- $\xi_3 \frac{(u\bar{d}e)^2}{M^5} \rightarrow$ d-9. Relevant for neutrinoless double beta decay

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$\boxed{\text{Dimension 5 and Dimension 9 operators are uncorrelated}}$

Contd

$\boxed{\text{Fundamental theory} \longrightarrow \text{Standard model effective Lagrangian}}$

- Additional source of lepton number violation in the full theory!!
- The lepton number violating particles of the full theory may contribute in neutrinoless double beta decay process

$$\Downarrow$$

$\boxed{\text{light } \nu \text{ contribution} + \text{ contribution from other L-violating states}}$

$\boxed{\text{Additional contibution suppressed?}}$

$\boxed{\text{This depends on the mass scale M of the other particles.}}$

Results

For lower mass-scale M, the additional contribution can be significantly large, and in-fact can saturate the Heidelberg- Moscow bound $T_{1/2} \geq 1.9 \times 10^{25} \mathrm{yrs}.$

Mohapatra 1986; Hirsch et al, 1995; Choi et al, 2002; Allanach et al, 2009.;

Tello, Nemevsek,Nesti, Senjanović, Vissani, 2011; Mitra, Senjanović, Vissani, 2012

$$\Downarrow$$

- In the simplest Type-I seesaw scenario which generates Majorana mass of light neutrinos, the heavy sterile neutrino states can saturate the neutrinoless double beta decay bound.

  Mitra, Senjanović, Vissani, NPB 856, 26, 2012

- Provided, the sterile states are relatively light

$$M \leq 10 \mathrm{GeV}$$

  to be consistent with radiative correction of neutrino mass.

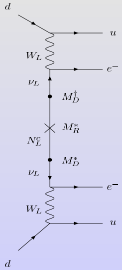
Heavy sterile neutrino exchange

n_h heavy Majorana neutrinos N_i $\rightarrow$ mixing V_{li} $\rightarrow$ mass M_i.

$M_i^2 > p^2 \sim (200)^2\mathrm{MeV}^2$; $p \rightarrow$ intermediate momentum

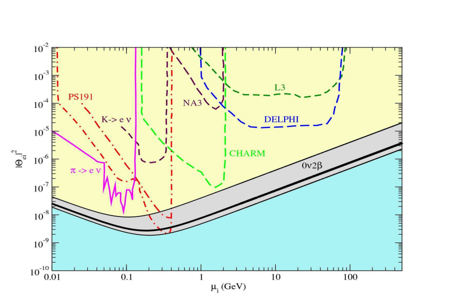
$$\boxed{\text{Half-life } \frac{1}{T_{1/2}} = G_{0\nu}\left|\mathcal{M}_\nu \eta_\nu + \mathcal{M}_N \eta_N\right|^2}$$

- $\eta_\nu = U_{ei}^2 m_i/m_e$, $\eta_N = V_{ei}^2 m_p/M_i$, $G_{0\nu} = 7.93 \times 10^{-15}$ yr^{-1}
- $\mathcal{M}_\nu$ and $\mathcal{M}_N \rightarrow$ nuclear matrix elements for light and heavy exchange



Bounds on active-sterile mixing

Bounds on active-sterile mixing angle from meson decays, sterile neutrino decays and neutrinoless double beta decay



A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP **0905**, 030 (2009);

Mitra, Senjanovic, Vissani, NPB **856**, 26 (2012)

$0\nu2\beta \rightarrow$ most stringent

- One order of magnitude improvement than the previous bound
- Updated nuclear matrix element, $\mathcal{M}_\nu = 5.24$ and $\mathcal{M}_N = 363$;

F. Simkovic, J. Vergados, A. Faessler,Phys. Rev. **D82**, 113015 (2010)

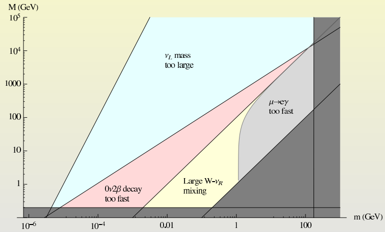
Active-sterile mixing $\frac{\Theta_{ei}^2}{M_i} \leq 7.6 \times 10^{-9}\ \mathrm{GeV}^{-1}$

Naive expectation from sterile neutrinos

Heavy sterile neutrinos N_i with Majorana mass matrix M_R

Mass matrix $M_n = \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}$

- $M_R \gg M_D$, the light Majorana mass
  $$M_\nu = M_D^T M_R^{-1} M_D$$
- Active-sterile mixing, $V = M_D^\dagger M_R^{-1\,*}$



Scale of $M_D \to m$, and Scale of M_R as M

Constraints from small neutrino mass rules out any prospect of lepton number violation in neutrinoless double beta decay coming from sterile sector, as well as sterile neutrino searches in colliders and lepton flavor violation.

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Light vs Heavy contribution

The amplitude is,

$$\mathcal{A}^* = \left[\frac{M_\nu}{p^2} - M_D^T M_R^{-1} M_R^{-1*} M_R^{-1} M_D + \mathcal{O}(M_R^{-5})\right]_{ee}$$

- The light contribution $\sim \frac{m^2}{M}\frac{1}{p^2}$, while the sterile contribution $\sim\frac{m^2}{M^3}$
- For $M^2 > p^2 \sim (200)^2 \mathrm{MeV}^2$, sterile contribution is expected to be suppressed.

- For multi generation, large neutrinoless double beta decay from sterile states can be achieved without any conflict with small neutrino mass
- Sterile neutrino contribution can be dominant as compared to the light neutrino contribution

Multiflavor scenario

Departure from seesaw condition

Vanishing seesaw condition $M_D^T M_R^{-1} M_D = 0$

- Neutrino mass as a perturbation of the vanishing seesaw condition $M_\nu = M_D^T M_R^{-1} M_D = 0$
- Light and sterile neutrino contributions in neutrinoless double beta decay are decoupled

Light neutrino mass matrix

Preferred choice of basis $\rightarrow$ Dirac diagonal basis

$$M_D = m \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix}; M_R^{-1} = M^{-1} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & \epsilon \end{pmatrix}$$

The light neutrino mass matrix

$$M_\nu \Rightarrow \frac{m^2}{M} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon^2 & \epsilon \\ 0 & \epsilon & \epsilon \end{pmatrix}$$

- $\epsilon \rightarrow$ perturbation
- In the limit $\epsilon \rightarrow 0$, $M_\nu \rightarrow 0$
- This way we get two massive light neutrinos

Contribution from the heavy states:

The sterile contribution in flavor basis is

For normal hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U_{e2}^* \sqrt{m_2} + U_{e3}^* \sqrt{m_3})^2}{m_2 + m_3}$$

For inverted hierarchy

$$(M_D^T M_R^{-3} M_D)^{\mathrm{F.l}}{}_{ee} = \xi \frac{m^2}{M^3} \times \frac{(U_{e2}^* \sqrt{m_2} + U_{e1}^* \sqrt{m_1})^2}{m_1 + m_2}$$

▸ more

Numerator and denominator depend same way on light neutrino mass

Sterile contribution is not suppressed by the light neutrino mass scale.

▸ more

How large sterile neutrino mass?

How large the sterile neutrino mass can be to saturate Heidelberg-Moscow bound?

$$M = 16\ \text{TeV} \times \left(\frac{T_{1/2}}{1.9 \times 10^{25}\text{yr}}\right)^{1/6} \left(\frac{\mathcal{M}_N \times \kappa}{363 \times 1}\right)^{1/3} \left(\frac{m}{174\ \text{GeV}}\right)^{2/3}$$

For $m = 174$ GeV, $T_{1/2} = 1.9 \times 10^{25}\mathrm{yrs}$, $\mathcal{M}_N = 363$ and

$\kappa = \mathcal{O}(1)$ sterile neutrinos of mass upto 16 TeV can saturate the $0\nu2\beta$ bound.

However

Small neutrino mass $\epsilon\frac{m^2}{M} < 0.1$ eV demands $\epsilon = 10^{-9}$

$\boxed{\text{Extreme fine-tuning condition}}$

- Simple scaling of M, m and ϵ by $\alpha < 1$

$$M \to \alpha \times M;\ m \to \alpha^{3/2} \times m;\ \epsilon \to \alpha^{-1} \times \epsilon$$

- Light neutrino mass $\epsilon \frac{m^2}{M}$ and the sterile contribution $\frac{m^2}{M^3}$ remains unchanged
- ϵ can be relatively large $\longrightarrow$ fine-tuning reduces

With lower value of sterile neutrino mass scale M, the fine tuning reduces

Still

Radiative stability of light neutrino masses?

What is the constrain on the sterile neutrino mass scale M, so that sterile neutrinos saturate $0\nu 2\beta$ bound and the light neutrino mass matrix is radiatively stable?

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Contd

- Sterile neutrinos saturates the Heidelberg-Moscow bound $T_{1/2} \geq 1.9 \times 10^{25}\mathrm{yrs}$
- Small neutrino mass, $\frac{\epsilon m^2}{M} < 0.1\mathrm{eV}$
- Radiative stability of light neutrino masses $\delta M_\nu < M_\nu$

Sterile neutrino mass scale is

$$M \lesssim \kappa^{1/4} \times 10 \text{ GeV}$$

κ can be be as large as $\kappa \sim \mathcal{O}(1)$

The upper bound on sterile neutrino mass is 10 GeV

Extended seesaw scenario

Dominant sterile neutrino contribution in other seesaw scenarios as well, e.g., Extended seesaw.

Additional sterile neutrino states N, S of equal generation.

$$M_n = \begin{pmatrix} 0 & 0 & M_D^T \\ 0 & \mu & M_S^T \\ M_D & M_S & M_R \end{pmatrix}$$

Kang, Kim, 2006; Majee, Parida, Raychaudhuri, 2008

- For $M_R > M_S > M_D \gg \mu$ and $\mu < M_S^T M_R^{-1} M_S$, light neutrino mass depend on small lepton number violating parameter μ. Sterile contribution is independent of μ.

$\boxed{\text{Light neutrino and sterile contribution is decoupled}}$

Conclusion

- We investigated the nature of $0\nu2\beta$ in Type-I seesaw
- Sterile neutrinos of mass upto 16 TeV can saturate the Heidelberg-Moscow neutrinoless double beta decay bound
- Light neutrinos has to be generated as a perturbation of vanishing seesaw condition
- The radiative stability of light neutrino mass matrix constrains the sterile neutrino mass scale to be less than 10 GeV
- We improved the bound on active-sterile mixing angle by one order of magnitude
- Dominant sterile contribution is possible to achieve for other non-minimal seesaw scenarios as well, *e.g.* Extended seesaw
- These are major exceptions to the Schechter-Valle "theorem"!

Thank you

Contd:

- Small neutrino mass $M_\nu = \frac{m^2}{M} < 0.1$ eV
- Saturating $0\nu 2\beta$ from sterile neutrinos,
  - $\frac{m^2}{M^3} = 7.6 \times 10^{-9} \mathrm{GeV}^{-1}$
- Heavy Majorana neutrino searches at LHC, $\theta = \frac{m}{M} \geq 10^{-2}$

  F. del Aguila *et al.* 2009; J. Kersten, A. Y. .Smirnov 2007
- Lepton flavor violation $\mu \to e\gamma$

back

Sterile neutrino contribution

$$\text{Dirac diagonal} \xrightarrow{O} \text{mass} \xrightarrow{U} \text{flavor}$$

The sterile neutrino contribution in flavor basis

$$\boxed{(M_D^T M_R^{-3} M_D)_{ee}^{Fl} = \kappa \ \frac{m^2}{M^3}}$$

- κ contains the information of mixings
- $\kappa = \xi \times \varphi^2$, with $\varphi = \sum_{i=1}^{3} U_{ei}^* O_{3i}$

back

Contd:

- Depending on $\frac{m^2}{M^3}$ factor, sterile neutrino contribution can saturate the bound
- $\frac{m^2}{M^3} \sim 7.6 \times 10^{-9}\ \mathrm{GeV}^{-1}$ to saturate $0\nu2\beta$ bound
- The light neutrino contributions,
  - For normal hierarchy $|(M_\nu)_{ee}| = |m_3 U_{e3}^2 - m_2 U_{e2}^2|$
  - For inverted hierarchy $|(M_\nu)_{ee}| = |m_2 U_{e2}^2 - m_1 U_{e1}^2|$

Dominating sterile neutrino contribution can be achieved, while the light neutrino contribution will be suppressed $\Rightarrow$ contrary to Schector-Valle theorem

back

Figure: One loop correction to the ν_L mass

Loop correction to light neutrino mass

- For $M < M_{ew} \rightarrow \delta M_\nu \sim \frac{g^2}{(4\pi)^2} \frac{m^2}{M} \frac{M^2}{M_{ew}^2}$
- For $M > M_{ew} \rightarrow \delta M_\nu \sim \frac{g^2}{(4\pi)^2} \frac{m^2}{M} \log(M_1/M_2)$

back

Extended seesaw

Non-minimal seesaw scenario, e.g.,

- Additional sterile neutrino states N, S of equal generation
- The mass matrix

$$M_n = \begin{pmatrix} 0 & 0 & M_D^T \\ 0 & \mu & M_S^T \\ M_D & M_S & M_R \end{pmatrix}$$

Kang, Kim, 2006; Majee, Parida, Raychaudhuri, 2008

- Assume,
  - $M_R > M_S > M_D \gg \mu$ and $\mu < M_S^T M_R^{-1} M_S$

Contd

- Light neutrino mass depends on μ

$$m_\nu \sim M_D^T (M_S^T)^{-1} \mu M_S^{-1} M_D$$

- The sterile contributions

$$\mathcal{A}_S = \left(\frac{M_D}{M_S}\right)^2 \frac{1}{m_s}$$
$$\mathcal{A}_N = \left(\frac{M_D}{M_R}\right)^2 \frac{1}{m_n}$$

- In the limit $\mu \to 0$, light neutrino masses vanishes
- Sterile contributions are independent of μ
- Light neutrino and sterile contribution in $0\nu 2\beta$ process are decoupled $\to$ sterile neutrinos can saturate the bound