P08

# Neutrinoless double beta decay in the seesaw mechanism

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## 1. Introduction

Puzzles of neutrino in SM

- ✓ Neutrino mass (oscillation experiment)
- ✓ Dirac type or Majorana type ?
- ✓ Right-handed neutrino …?

Oscillation experiment data [NuFIT 5.1('21)]

| Neutrino mass hierarchy | $\Delta m_{21}^2/10^{-5}eV^2$ | $\Delta m_{3l}^2/10^{-3}eV^2$ |
|---|---|---|
| NH $(m_1 < m_2 < m_3)$ | $7.42^{+0.21}_{-0.20}$ | $2.510^{+0.027}_{-0.027}$ |
| IH $(m_3 < m_1 < m_2)$ | $7.42^{+0.21}_{-0.20}$ | $-2.490^{+0.026}_{-0.028}$ |

$l$ : index of lightest active neutrino

- At least two generations of neutrinos are massive.
- Smallness of neutrino mass,

$$m_\nu \sim \mathcal{O}(10^{-11})\text{GeV} \ll m_e \sim 10^{-4}\text{GeV}$$

$m_\nu$ : active neutrino mass
$m_e$ : electron mass

**Beyond SM physics is needed to explain these discrepancies**

## 2. SM + RHν

$F_{\alpha I}$ : Yukawa coupling $L_\alpha$ : SM lepton doublet $\Phi$ : SM Higgs doublet
$\nu_{RI}$ : right-handed neutrino $M_I$ : Majorana mass of right-handed neutrino

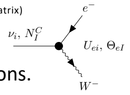
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{\nu_{RI}}\gamma^\mu\partial_\mu\nu_{RI} - \left(F_{\alpha I}\overline{L_\alpha}\Phi\nu_{RI} + \frac{M_I}{2}\overline{\nu^c_{RI}}\nu_{RI} + h.c.\right)$$

Weak interaction of neutrino [Pontecorvo('58)] [Maki, Nakagawa, Sakata ('62)]

$$\nu_{L\alpha} = \sum_i U_{\alpha i}\nu_i + \sum_I \Theta_{\alpha I} N_I^c$$

$U_{\alpha i}$ : Mixing element of active ν (PMNS matrix)
$\Theta_{\alpha I}$ : Mixing element of RHν

All mass eigenstates have the weak interactions.



Yukawa coupling [Casas, Ibarra('01)]

$$F = \frac{i}{\langle\Phi\rangle} U D_\nu^{1/2}\Omega D_N^{1/2}$$

$\omega$ : Complex parameter

$D_\nu = \text{diag}(m_1, m_2, m_3)$
$D_N = \text{diag}(M_1, M_2)$

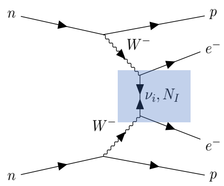
$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$$

**Seesaw mechanism** works!
Assumption for Dirac mass & Majorana mass $M_D (\equiv \langle\Phi\rangle F) \ll M_I$ [P. Minkowski ('77)]

Predictions
- Majorana neutrino
- Smallness of neutrino masses
- New particles and interactions

## 3. 0νββ decay

Why is 0νββ decay?



- One possibility for the decay is Majorana neutrino mediation.
  → It is possible to verify the Majorana nature of the neutrino.
- The decay process violates the lepton number.
  → Application to Leptogenesis is expected.

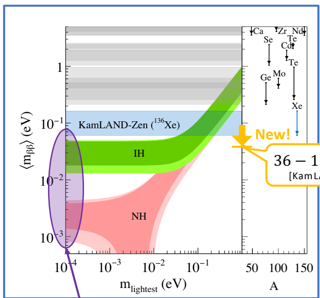
Effective mass

$$m_{\rm eff} = m_{\rm eff}^\nu + m_{\rm eff}^N$$

Active ν's contribution $m_{\rm eff}^\nu = \sum_i U_{ei}^2 m_i$

RHν's contribution $m_{\rm eff}^N = \sum_I \Theta_{eI}^2 M_I f_\beta(M_I)$

Active ν's contribution [KamLAND-Zen ('16)]




Suppression factor by the propagator
[Faessler, Gonzalez, Kovalenko, Simkovic('14)] [Barea, Kotila, Iachello('15)]

$$f_\beta(M_I) = \frac{\Lambda_\beta^2}{\Lambda_\beta^2 + M_I^2}$$

**When $M_I \ll \Lambda_\beta$, RHν great contribution!!**

Testable region $m_{\rm lightest} = 0$

$$|m_{\rm eff}^\nu| = \begin{cases} 1.45 - 3.68 \text{ meV (NH)} \\ 18.6 - 48.4 \text{ meV (IH)} \end{cases}$$

## 4. 0νββ decay in the seesaw mechanism

Cancellation by N

Mass assumption $M_1 < \Lambda_\beta \ll M_2$ $\begin{pmatrix} f_\beta(M_1) = 1-\delta_f^2 \\ f_\beta(M_2) = 0 \end{pmatrix}$

The effective mass can be expanded into a concrete expression by using Casas-Ibarra parametrization.

NH case ($m_1 = 0$)

$$m_{\rm eff} = \sum_i U_{ei}^2 m_i + \sum_I \Theta_{eI}^2 M_I f_\beta(M_I)$$
$$= [1 - f_\beta(M_1)]\left[U_{e2}m_2^{1/2}\cos\omega + U_{e3}m_3^{1/2}\sin\omega\right]^2 + [1 - f_\beta(M_2)]\left[U_{e2}m_2^{1/2}\sin\omega - U_{e3}m_3^{1/2}\cos\omega\right]^2$$
$$= \left(U_{e2}m_2^{1/2}\sin\omega - U_{e3}m_3^{1/2}\cos\omega\right)^2 + \left(U_{e2}m_2^{1/2}\cos\omega + U_{e3}m_3^{1/2}\sin\omega\right)^2 \times \delta_f^2$$

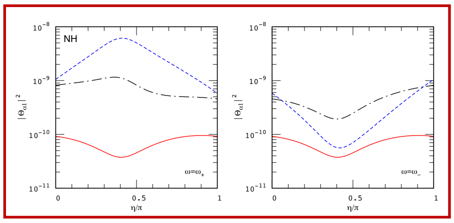
= 0

solved

$$\tan\omega = \frac{A \pm i\delta_f}{1 \mp i\delta_f A} \equiv \tan\omega_\pm$$
$$A = \frac{U_{e3}m_3^{1/2}}{U_{e2}m_2^{1/2}}$$

**Decay suppressed by the RHν!!**

**Even if no decay is observed, the nature of RHν can be characterized!**



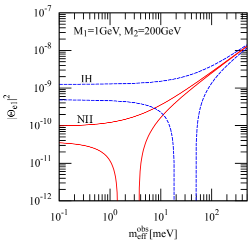
Enhancement by N

Assuming the effective mass observed at $|m_{\rm eff}| = m_{\rm eff}^{\rm obs}$

Mass assumption $M_1 \neq M_2$

- The absolute value of the mixing element is determined by the effective mass of the observed decay.

$$\Theta_{e1}^2 = \frac{m_{\rm eff} - m_{\rm eff}^\nu[1 - f_\beta(M_2)]}{M_1[f_\beta(M_1) - f_\beta(M_2)]}$$

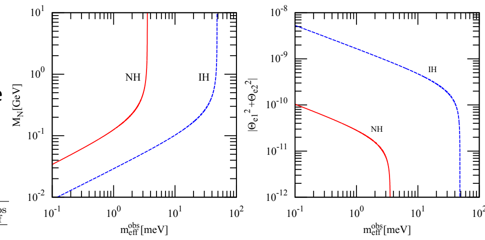



Mass assumption $M_1 = M_2 = M_N$

- Predictions are obtained regarding the absolute value of the sum of the mixing elements and the mass of the RHν.

$$M_N = \Lambda_\beta\sqrt{\frac{m_{\rm eff}^{\rm obs}}{|m_{\rm eff}^\nu| - m_{\rm eff}^{\rm obs}}}$$

$$|\Theta_{e1}^2 + \Theta_{e2}^2| = \frac{|m_{\rm eff}^\nu|}{\Lambda_\beta}\sqrt{\frac{|m_{\rm eff}^\nu| - m_{\rm eff}^{\rm obs}}{m_{\rm eff}^{\rm obs}}}$$




## 5. Future experiments

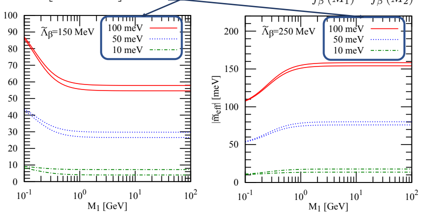
Effective mass of the decay observed for nuclei with $\Lambda_\beta$ = 200 MeV.

The effective masses of the decays including N's contribution becomes different depending on the decay nuclei.
→ The nature of RHν is more limited.

Fermi momentum of nuclei
$^{76}$Ge : 159.0 – 193.0 MeV
$^{136}$Xe : 178.0 – 211.0 MeV
[Faessler, Gonzalez, Kovalenko, Simkovic('14)]

Predicted effective mass

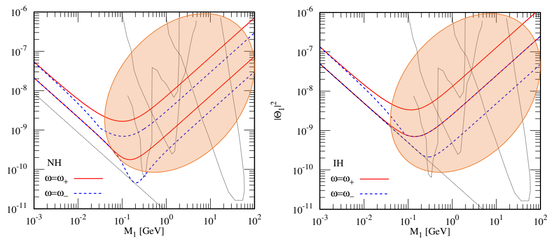
$$\tilde{m}_{\rm eff} = \left[1 - \tilde{f}_\beta(M_2)\right] m_{\rm eff}^\nu + \left[m_{\rm eff} - m_{\rm eff}^\nu[1 - f_\beta(M_2)]\right]\frac{\tilde{f}_\beta(M_1) - \tilde{f}_\beta(M_2)}{f_\beta(M_1) - f_\beta(M_2)}$$




## 6. Conclusion

- We discussed the 0νββ decay in the seesaw mechanism.
- We comprehensively investigated the contribution to the decay of the RHν.
- Especially, when it is lighter than the typical fermi momentum, the decay is strongly suppressed and may no longer occur.
- We showed that the properties of RHν may be characterized by the future decay-observation-experiments.
- We pointed out that multiple experiments using different nuclei are important to understand the properties of right-handed neutrinos (masses and mixing elements).

Huge region can be searched on future experiments.

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