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The effect of right-handed currents and dark side of the solar neutrino parameter space to Neutrinoless Double Beta Decay

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Abstract. We discuss how dark side of the solar neutrino parameter space and effect of new physics contributions from right-handed currents can reveal the Majorana nature of neutrinos by the observation of the rare process called neutrinoless double beta decay, i.e. the simultaneous decay of two neutrons in the nucleus of an isotope (A, Z) into two protons and two electrons without the emission of any neutrinos i.e.$(A, Z) \rightarrow (A, Z+2) + 2e^-$. While the standard mechanism of neutrinoless double beta decay with exchange of light Majorana neutrinos, normal ordering and inverted ordering can not saturate the present experimental limit, and quasi-degenerate light neutrinos are strongly disfavored by cosmology, we consider new physics contributions due to right-handed charged current effects arising in TeV scale left-right symmetric model which can satuare the experimental bound provided by KamLAND-Zen and GERDA.

Keywords: Solar Neutrino, Neutrinoless double beta decay, Majorana neutrinos.

1. INTRODUCTION

The recent neutrino oscillation experiments revealed that neutrinos have non-zero masses and mixing, which calls for new physics beyond the standard model as the standard model of particle physics predicts massless neutrinos. On the other hand, neutrinoless double beta decay($0\nu\beta\beta$) is a unique phenomenon whose experimental observation would reveal whether neutrinos are Majorana particles [1] which violates Lepton Number. Majorana particles are their own antiparticles. All the fermions present in the standard model are of Dirac type and only the neutrino, being neutral, can become the Majorana particle. The main parameter of $0\nu\beta\beta$ is effective Majorana mass(m_{ee}) that depends upon the absolute mass and mass ordering of the neutrino i.e. whether the neutrino mass follows normal ordering (NO) in which third mass eigenstate is the heaviest or inverted ordering (IO) in which the third mass eigenstate is lightest. This process also has the potential to tell us about the absolute mass scale and mass ordering of neutrino. So Scientists around the world are putting in enormous effort, and different experiments are going on to tell us about $0\nu\beta\beta$ process. No positive signal has been observed yet in any of the experiment. But lower limit on the half-life

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($T_{1/2}$) on neutrinoless double beta decay of different isotope i.e. $T_{1/2}(Xe^{156}) > 1.5 \times 10^{25}$yrs from KAMLAND-Zen[39], $T_{1/2}(Ge^{76}) > 8 \times 10^{25}$yrs from GERDA[46] and $T_{1/2}(Te^{130}) > 1.5 \times 10^{25}$ yrs from the combined result of CURCINO & CUORE[41] has been found with 90% C.L .

The discovery of neutrino oscillation, which gives the evidence of neutrino masses and mixing, has an enormous impact on our perception about the understanding of the universe. In the study of particle physics, the most successful and well-accepted theory is the standard model (SM) of the particle physics that has been found to agree with almost all experimental data up to current accelerator energy. All of the particles present in the SM have been experimentally observed. Despite the immense success of the SM, it fails to explain some of the fundamental questions like non zero neutrino mass, the mystery of dark matter and matter-antimatter asymmetry of the universe. So we have to think beyond the standard model (BSM) of particle physics to explain all the shortcoming of SM.

A well-motivated candidates of physics beyond the standard model is Left-Right Symmetric Model (LRSM)[33–36]. It contains additional right-handed current compare to the SM. It explains light neutrino mass via seesaw mechanism by normally adding right-handed neutrino to the model which are absent in the SM of particle physics. It also provides the theoretical origin of maximal parity violation which is observed in weak interactions while remaining conserved in strong and electromagnetic interactions. It is based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Here the right-handed neutrino is the necessary part of the model. Neutrinos acquire their mass from both Type-I and Type-II seesaw mechanism that arises naturally in the LRSM.

Neutrino oscillation experiments provide information about mass squared differences and mixing angles i.e. ($\Delta m^2, sin^2 2\theta$). Here we always use ($0 \leq \theta \leq \pi/4$), which is called the "light side" of the parameter space. However, it misses the other half of the parameter space ($\pi/4 < \theta \leq \pi/2$), which is called the "dark side"[44]. Neutrino oscillation in vacuum depends on $sin^2 2\theta$, which is equivalent for both light and dark sides of the parameter space. That's why we only use the light side of the parameter space. But in the case of matter effect i.e. non-standard neutrino interactions (NSI)[42, 43], the dark side and the light side are physically inequivalent. The light side solution to the solar neutrino problem is generally called standard large mixing angle i.e LMA solution, whereas the dark side solution to the solar neutrino problem is called as Dark-LMA i.e DLMA solution.

In this paper, we study the effect of DLMA solution to the solar neutrino problem on neutrinoless double beta ($0\nu\beta\beta$) decay for both of these standard and right-handed current mechanisms and compare them with the standard LMA solution to the solar neutrino problem on $0\nu\beta\beta$ for both mechanisms. This knowledge will help the future experiments to probe different energy range of effective mass and find out the sensitivity on $0\nu\beta\beta$.

2. STANDARD MECHANISM OF NEUTRINOLESS DOUBLE BETA DECAY

Standard model of particle physics is based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. It contains only left-handed neutrino. Right-handed neutrino is absent in the standard model of particle physics. Different experiments have found the half-life of different isotopes for $0\nu\beta\beta$. So for standard mechanism, the inverse half-life ($T_{1/2}$) for $0\nu\beta\beta$ is given as

$$[T_{1/2}]^{-1} = G\left|\frac{M_\nu}{m_e}\right|^2 |m^\nu_{ee}|^2 \tag{1}$$

where G is the phase factor, M_ν is the nuclear matrix element, m_e is the mass of electron and m^ν_{ee} is the effective majorana mass. We know the value of G and M_ν of different isotopes. So the main parameter of interest in $0\nu\beta\beta$ is the effective majorana mass(m^ν_{ee}) which is the combination of neutrino mass eigenvalues and neutrino mixing matrix element. The effective majorana mass is given by

$$m^\nu_{ee} = \left|\sum_{i=1}^{3} U^2_{ei} m_i\right| \tag{2}$$

where U is the unitary PMNS mixing matrix and m_i is the mass eigenvalues.
PMNS mixing matrix U is given by

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{i\alpha}{2}} & 0 \\ 0 & 0 & e^{\frac{i\beta}{2}} \end{pmatrix} \tag{3}$$

where $c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$,$\delta$ is the CP violation phases and α, β are majorana phases.
if we put the value of mixing matrix U in eq.2 , then effective mass is

$$m^\nu_{ee} = \left|m_1 c^2_{12} c^2_{13} + m_2 s^2_{12} c^2_{13} e^{i\alpha} + m_3 s^2_{13} e^{i\beta}\right| \tag{4}$$

Here, the effective mass depends upon the neutrino oscillation parameter θ_{12},θ_{13} and the neutrino mass eigenvalues m_1, m_2 and m_3 for which we don't know the absolute value but we know the mass squared differences between them. and we don't know anything about the majorana phases.
we know the value of Δm^2_{sol}, which is $\Delta m^2_{sol}(\Delta m^2_{21}) = m^2_2 - m^2_1$, it has a positive sign so always $m_2 > m_1$. and we don't know the sign of $m^2_{atm}(\Delta m^2_{31})$, which allows for two possible ordering of neutrino mass i.e.

$$\begin{aligned} \Delta m^2_{atm}(\Delta m^2_{31}) &= m^2_3 - m^2_1, \text{for Normal Ordering(NO)} \\ &= m^2_1 - m^2_3, \text{for Inverted Ordering(IO)} \end{aligned}$$

Normal Ordering (NO) : $m_1 < m_2 << m_3$

$$\text{Here, } m_1 = m_{\text{lightest}} \; ; \; m_2 = \sqrt{m_1^2 + \Delta m_{sol}^2} \; ;$$
$$m_3 = \sqrt{m_1^2 + \Delta m_{sol}^2 + \Delta m_{atm}^2} \tag{5}$$

Inverted Ordering (IO) : $m_3 << m_1 < m_2$

$$\text{Here, } m_3 = m_{\text{lightest}} \; ; \; m_1 = \sqrt{m_3^2 + \Delta m_{atm}^2} \; ;$$
$$m_2 = \sqrt{m_3^2 + \Delta m_{atm}^2 + \Delta m_{sol}^2} \tag{6}$$

Oscillation Parameters	within 3σ range ([29])
$\Delta m_{21}^2[10^{-5}\text{eV}^2]$	7.05-8.14
$\lvert\Delta m_{31}^2(\text{NO})\rvert[10^{-3}\text{eV}^2]$	2.41-2.60
$\lvert\Delta m_{31}^2(\text{IO})\rvert[10^{-3}\text{eV}^2]$	2.31-2.51
$\sin^2\theta_{12}$	0.273-0.379
$\sin^2\theta_{13}(\text{NO})$	0.0196-0.0241
$\sin^2\theta_{13}(\text{IO})$	0.0199-0.0244

Table 1. The oscillation parameters like mass squared differences and mixing angles within 3σ range.[29]

In this paper, we symbolize θ_{D12} for the DLMA solution in presence of NSI and θ_{12} as the standard LMA solution. The 3σ range of both θ_{12} and θ_{D12} are given in Table.2 [29, 30]. By varying all the neutrino oscillation parameters in their 3σ ranges and varying the Majorana phases α and β from 0 to 2π range, we obtained the plot of effective mass as a function of lightest neutrino mass i.e. m_1,m_3 for NO and IO respectively in Fig.1 .

We plot the effective mass by putting LMA and DLMA solution for both NO and IO in Fig.1. Here, the gray band($0.07 - 0.16$ eV) refers to the current upper limit obtained from the combined result of KamLAND-Zen and GERDA[46]. The region above this is disallowed. and the yellow region is disallowed by the cosmological constraints on the sum of light neutrino masses[31] .

From the Fig.1, For NO, we found out that m_{ee}^{ν} for the DLMA solution is shifting into the region between the NO and IO of LMA solution which is called as the desert region and m_{ee}^{ν} for

	$sin^2\theta_{12}$	$sin^2\theta_{D12}$
min	0.273	0.650
max	0.379	0.725

Table 2. LMA and DLMA solution for θ_{12} to the solar neutrino problem.

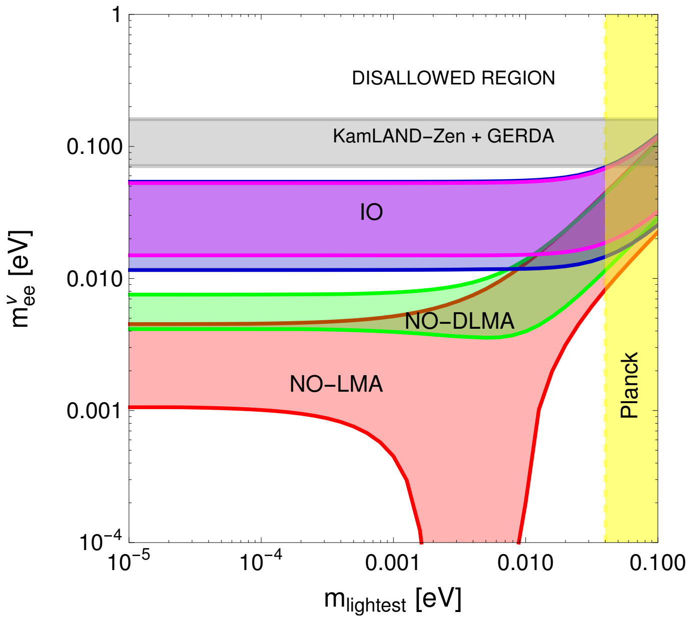

Figure 1. Effective majorana mass m^{ν}_{ee} for neutrinoless double beta decay as a function of lightest neutrino mass for standard mechanism. Here the red and green band correspond to the solution of θ_{12} and θ_{D12} for NO , blue and magenta band correspond to the solution of θ_{12} and θ_{D12} for IO.

the DLMA solution is found out to be higher than that of LMA solution. and when the $m_{\rm lightest}$ increases, the overlap region between the LMA and DLMA solution also increases. For $m_{\rm lightest} \in [10^{-3}, 10^{-2}]$eV, we found that the minimum value of m^{ν}_{ee} for LMA solution is very small i.e. it nearly vanishes. But for DLMA solution, in that region the minimum value of m^{ν}_{ee} remains the same as the value when $m_{\rm lightest} < 10^{-3}$eV for NO.
But in case of IO, the maximum value of m^{ν}_{ee} for both LMA and DLMA solution remain same. whereas the minimum value of m^{ν}_{ee} for DLMA solution is slightly higher than the LMA solution which is nearly same. The overlap region between LMA and DLMA solution remains the same throughout the value of $m_{\rm lightest}$. Here The DLMA solution fully overlaps with the LMA solution. No considerable change is found between both of these solutions for IO. So m^{ν}_{ee} remains the same for both LMA and DLMA solution in IO.

3. RIGHT-HANDED CURRENT EFFECTS TO NEUTRINOLESS DOUBLE BETA DECAY

We believe that lepton number violating $0\nu\beta\beta$ transitions could be induced either by standard mechanism due to the exchange of light Majorana neutrinos discussed in previous section or by corresponding new interactions. Since we have already found that standard mechanism can not saturate the present experimental bound one has to go beyond SM framework and there exist many models contributing to neutrinoless double beta decay [2–5, 11, 15, 17, 18, 20, 22, 23, 26]. In the present work, we have considered new interactions arising from purely right-handed currents within left-right symmetric models – parametrized in terms of the effective mass parameter or the half-life of the nucleus – which can saturate the current experimental bounds and one can derive limits for light Majorana neutrino masses, right-handed Majorana neutrinos, right-handed charged gauged boson mass M_{W_R} and its mixing with the left-handed counterpart gauge boson and the corresponding gauge coupling g_R.

We consider a left-right symmetric model with Type-II seesaw dominance[32, 37, 38] where symmetry breaking occurred at TeV scale leading to right-handed charged gauge boson W_R and right-handed neutrino N_R mass in the order of TeV scale. This leads to new physics contribution to $0\nu\beta\beta$ due to right-handed current via $W_R - W_R$ mediation and heavy neutrino exchange.

When we considered LRSM with Type-II seesaw dominance, the mass eigenvalues of the left and right handed neutrinos are proportional to each other,

$$m_L \propto M_R \tag{7}$$

As a result of this, the left and right handed neutrinos have the same PMNS mixing matrix.

$$U_L^{PMNS} = V_R^{PMNS} \tag{8}$$

and the mass eigenvalues are related as follows: **Normal Ordering (NO)**($m_1 = m_{\rm lightest}$)

$$m_2 = \sqrt{m_1^2 + \Delta m^2_{sol}}\ ;\ m_3 = \sqrt{m_1^2 + \Delta m^2_{sol} + \Delta m^2_{atm}}\ ,$$

$$M_1 = \frac{m_1}{m_3} M_3 \; ; \; M_2 = \frac{m_2}{m_3} M_3 \tag{9}$$

Here we fixed the heaviest right-handed neutrino mass M_3 for NO.

Inverted Ordering (IO)($m_3 = m_{\text{lightest}}$)

$$\begin{aligned} m_1 &= \sqrt{m_3^2 + \Delta m_{atm}^2} \; ; \; m_2 = \sqrt{m_3^2 + \Delta m_{atm}^2 + \Delta m_{sol}^2} \,, \\ M_1 &= \frac{m_1}{m_2} M_2 \; ; \; M_3 = \frac{m_3}{m_2} M_2 \end{aligned} \tag{10}$$

Here we fixed the heaviest right-handed neutrino mass M_2 for IO.

When we considered the LRSM with Type-II see saw dominance where the effect of purely right handed current along with standard mechanism is taken into consideration, the inverse half-life of a given isotope for $0\nu\beta\beta$ is given by

$$\begin{aligned} [T_{1/2}]^{-1}_{LR} &= G \left| \frac{M_\nu}{m_e} \right|^2 (|m_{ee}^\nu|^2 + |m_{ee}^N|^2) \\ &= G \left| \frac{M_\nu}{m_e} \right|^2 |m_{ee}^{\nu+N}|^2 \end{aligned} \tag{11}$$

where m_{ee}^ν is the effective mass arising due to left-handed neutrino in standard mechanism and m_{ee}^N is the effective mass arising due to purely right handed current. Also, here $|m_{ee}^{\nu+N}|^2 = |m_{ee}^{LR}|^2 = |m_{ee}^\nu|^2 + |m_{ee}^N|^2$,where m_{ee}^{LR} is the total effective mass arising due to right-handed current in LRSM. We know the expression for m_{ee}^ν that is given in eq.4 and the expressions for m_{ee}^N is given by

$$\begin{aligned} m_{ee}^N &= \frac{C_N}{M_3} \left| c_{12}^2 c_{13}^2 \frac{m_3}{m_1} + s_{12}^2 c_{13}^2 \frac{m_3}{m_2} e^{i\alpha} + s_{13}^2 e^{i\beta} \right| \text{ (NO)} \\ &= \frac{C_N}{M_2} \left| c_{12}^2 c_{13}^2 \frac{m_2}{m_1} + s_{12}^2 c_{13}^2 e^{i\alpha} + s_{13}^2 \frac{m_2}{m_3} e^{i\beta} \right| \text{ (IO)} \end{aligned}$$

where $C_N = \langle p^2 \rangle \left(\frac{g_R}{g_L}\right)^4 \left(\frac{M_{W_L}}{M_{W_R}}\right)^4$. Here typical momentum transfer $\langle p \rangle \approx 100$ MeV , g_R & g_L are the coupling constants of $SU(2)_L$ & $SU(2)_R$ respectively and M_{W_L} & M_{W_R} are the masses of the left and right-handed gauge bosons i.e W_L and W_R respectively that mediate the process. In this paper, we denote M_N as the heaviest right-handed neutrino mass eigenvalue i.e. M_3 for NO and M_2 for IO.

In the present work, we have considered $g_R \approx g_L$,$M_N = 1$ TeV,$M_{W_L} = 80.379$ GeV and $M_{W_R} \approx 3.5$ TeV [45]. By varying all the oscillation parameters in their 3σ range[29] and Majorana phases from 0 to 2π, we obtained the plot of effective mass (m_{ee}^{LR}) as a function of lightest neutrino mass for NO and IO by using both LMA and DLMA solution in Fig.2 .

From the Fig.2, For NO, we found that the effective mass(m_{ee}^{LR}) remains nearly the same for the higher value of absolute mass i.e. $m_{\text{lightest}} > 0.03$ eV, but that region is disfavoured by the cosmological constraint. We observed that both the LMA and DLMA solutions for NO saturate the higher value of effective mass limit provided by KamLAND-Zen and GERDA so that we can

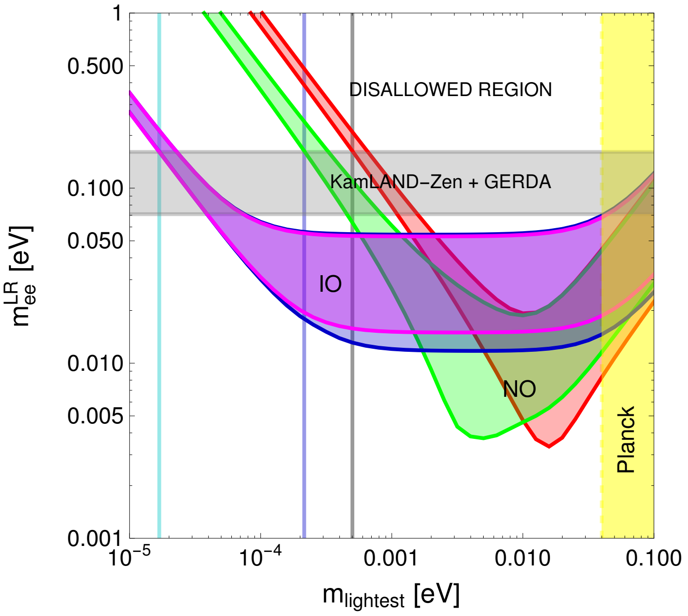

Figure 2. effective majorana mass m_{ee}^{LR} for neutrinoless double beta decay as a function of lightest neutrino mass from the contribution of right handed current.Here the red and green band correspond to the solution of θ_{12} and θ_{D12} for NO, blue and magenta band correspond to the solution of θ_{12} and θ_{D12} for IO.

find the lower limit of absolute mass of the lightest neutrino. Here DLMA solution (Green band) is shifted towards the left as compared to the LMA solution (Red band) implying that the lower limit of absolute mass for DLMA solution is comparatively smaller than the lower limit of absolute mass for LMA solution. But the m_{ee}^{LR} range is the same for both of these solutions for NO. So the lower limit of absolute mass of the lightest neutrino for NO is found out to be

$$m_{\text{lightest}} > 5.01 \times 10^{-4} \text{ (for LMA solution)}$$

$$m_{\text{lightest}} > 2.15 \times 10^{-4} \text{ (for DLMA solution)}$$

In case of IO, m_{ee}^{LR} remains the same for both LMA and DLMA solutions. So both of these solutions are equal for IO. Here also both of these solutions saturate the higher value of m_{ee}^{LR}. As both LMA and DLMA solutions are equal for IO, we found the same lower limit of m_{lightest} for both of these solutions. The lower limit of absolute mass of the lightest neutrino for IO is found to be

$$m_{\text{lightest}} > 1.685 \times 10^{-5} \text{ (IO)}$$

which is very small as compared to the lower limit of absolute mass of lightest neutrino for both LMA and DLMA solutions for NO.

4. CONCLUSION

If the $0\nu\beta\beta$ process happens, it will address many unsolved fundamental questions of physics like Majorana nature of the neutrino, matter-antimatter asymmetry, absolute mass scale and mass ordering of neutrino which will help us for the better understanding of the universe. So searching for this rare process is of paramount importance. From the standard mechanism, we found out that the DLMA solution for NO is shifting into the desert region ($0.004 - 0.0075$ eV) which provides a new sensitivity goal for the future experiments. If we find any positive signal for $0\nu\beta\beta$ in that desert region, this will confirm the DLMA solution to the solar neutrino problem as well. From the right-handed current mechanism, we found that both LMA and DLMA solutions to the solar neutrino problem for both NO and IO saturate the experimental limit provided by KamLAND-Zen and GERDA, which also provide the lower limit of absolute mass of lightest neutrino that is not provided by the standard mechanism. So if we find any positive signal for $0\nu\beta\beta$ above the region of IO in the standard mechanism, we have to consider the contribution from the right-handed current as well.

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