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

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The Majorana nature of neutrinos will be the confirmed by the observation of the rare process called as neutrinoless double beta decay process, i.e. the simultaneous decay of two neutrinos in the nucleus of an isotope $\left(A, Z\right)$ into two protons and two electrons without the emission of any neutrinos i.e. $\left(A, Z\right) \rightarrow \left(A, Z + 2\right) + 2e^−$. The non-observation of such a decay so far has been interpreted as a lower limit on the half life of the isotope under investigation, which puts severe constraints on any new physics giving rise to LNV in the electron sector. On the other hand, the standard mechanism with normal ordering and inverted ordering can not saturate the present experimental limit while quasi-degenerate light neutrinos are strongly disfavored by the upper limits on the sum of light neutrino masses from cosmological data sets. In this work, we show that how dark side of the solar neutrino parameter space and effect of new physics contributions from right-handed currents can saturate the experimental limit provided by KamLAND-Zen and GERDA.

I. 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 standard model of particle physics predicts massless neutrinos. On the other hand, neutrinoless double beta decay($0\nu\beta\beta$) is an unique phenomena whose experimental observation would reveal whether neutrinos are Majorana particles which violates Lepton Number. Majorana particles are its own antiparticles. All the fermions present in the standard model are of Dirac type and only the neutrino, being neutral, have the possibility to 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 follow normal ordering(NO) in which third mass eigen state is the heaviest or inverted ordering(IO) in which the third mass eigenstate is lightest. This process have also the potential to tell us about the absolute mass scale and mass ordering of neutrino. So Scientists around the world give their enormous effort and different experiments are going on to tell us about $0\nu\beta\beta$ process. There is no positive signal has been observed yet in the experiment. But lower limit of the half life($t_{1/2}$) on neutrinoless double beta decay of different isotope i.e $t_{1/2}(Xe^{136}) > 1.5 \times 10^{25}\text{yrs}$ from KAMLAND-Zen, GERDA and $t_{1/2}(Te^{130}) > 1.5\times 10^{25}\text{yrs}$ from the combined result of CURCINO & CUORE has been found out with 90% C.L. After the discovery of neutrino oscillation, which gives the evidence of neutrino mass and mixing that have 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 particle present in the SM have been experimentally observed. Despite the immense success of the SM, it fails to explain some of the fundamental question like non zero neutrino mass, mystery of dark matter and matter antimatter asymmetry of the universe. So we have to think beyond the standard model(BSM) of particle physics in order to explain all the shortcoming of SM. A well motivated candidates of physics beyond the standard model is Left Right Symmetric Model(LRSM). It contains additional right handed current compare to the SM. It explains light neutrino mass via see saw mechanism by normally adding right handed neutrino to the model that absent in the SM of particle physics. It also provides the theoretical origin of maximal parity violation that observed in weak interaction while conserved in strong and electromagnetic interaction. It is based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)\text{B-L}$. Here the right handed neutrino are the necessary part of the model. Neutrino acquire their mass from both type I and type II see saw mechanism that arises naturally in the LRSM.

Neutrino oscillation experiments provides information about mass square differences and mixing angles i.e. $(\Delta m^2, \sin^22\theta)$. Here we always use $0 \leq \theta \leq \pi/4$, which is called the “light side” of the parameter space. However, we misses the other half of the parameter space $\left(\pi/4 < \theta \leq \pi/2\right)$ which is called “dark side” [11]. Neutrino oscillation in vacuum depends on the $\sin^22\theta$ which is equivalent for both light and dark side 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 interaction(NSI) [13, 14] the dark side and the light side are physically inequivalent. The light side solution to the solar neutrino problem generally called standard large mixing angle i.e LMA solution , where as the dark side solution to the solar neutrino problem 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 mechanism and compare them with the standard LMA solution to the solar neutrino problem on $0\nu\beta\beta$ for both mechanism. This knowledge helps the future experiment to probe in the different energy range of effective mass and find out the sensitivity on $0\nu\beta\beta$.

II. STANDARD MECHANISM OF NEUTRINOLESS DOUBLE BETA DECAY

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

$$[t_{1/2}]^{-1} = G |M_e|^2 |m_{ee}|^2$$

(1)

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

$$m_{ee}^\nu = \sum_{i=1}^{3} U_{ei}^2 m_i$$

(2)

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

PMNS mixing matrix $U$ is given by

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

(3)

where $c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}, \delta$ is the CP violation phases and $\alpha, \beta$ are majorana phases.

If we put the value of mixing matrix $U$ in eq. ?? , then effective mass is,

$$m_{ee}^\nu = |m_{11}^2 c_{13}^2 + m_{22} s_{12}^2 e^{i\alpha} + m_{33} s_{12}^2 e^{i\beta}|$$

(4)

Here, effective mass depends upon the neutrino oscillation parameter $\theta_{12}, \theta_{13}$ 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 square difference between them. and we don’t know anything about the majorana phases. we know the value of $\Delta m^2_{sol}$ which is $\Delta m^2_{sol}(\Delta m^2_{31}) = m_3^2 - m_1^2$ has a positive sign so always $m_2 > m_1$, and we don’t know the sign of $\Delta m^2_{atm}(\Delta m^2_{31})$, which allows two possible ordering of neutrino mass i.e

$$\Delta m^2_{atm}(\Delta m^2_{31}) = m_3^2 - m_1^2, \text{ for Normal Ordering(NO)}$$

$$= m_1^2 - m_2^2, \text{ for Inverted Ordering(IO)}$$

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

Here, $m_1 = m_{lightest}; m_2 = \sqrt{m_1^2 + \Delta m^2_{sol}} ;$

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

(5)

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

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

$$m_2 = \sqrt{m_2^2 + \Delta m^2_{atm} + \Delta m^2_{sol}}$$

(6)

Oscillation Parameters within 3σ range

|                  | (12) | (13) |
|------------------|------|------|
| $\Delta m^2_{21}$| $10^{-4}$eV$^2$ | 7.05-8.14 |
| $|\Delta m^2_{31}(NO)|$| $10^{-3}$eV$^2$ | 2.41-2.60 |
| $|\Delta m^2_{31}(IO)|$| $10^{-3}$eV$^2$ | 2.31-2.51 |
| $\sin^2\theta_{12}$ | 0.273-0.379 |
| $\sin^2\theta_{13}(NO)$ | 0.0196-0.0241 |
| $\sin^2\theta_{13}(IO)$ | 0.0199-0.0244 |

TABLE I: The oscillation parameters like mass squared differences and mixing angles within 3σ range.

In this paper, we symbolize $\theta_{D12}$ for the DLMA solution in presence of NSI and $\theta_{D12}$ as the standard LMA solution. The 3σ range of both $\theta_{12}$ and $\theta_{D12}$ are given in Table II[12,13]. By varying all the neutrino oscillation parameter in their 3σ ranges and varied the majorana phases $\alpha$ and $\beta$ 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[3]. The region above this are disallowed, and the yellow region is disallowed by the cosmological constraints on the sum of light neutrino masses[14].
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 \cite{15,26}. In the present work, we have considered new interactions are arising from purely right-handed currents within left-right symmetric models – parametrized in terms of effective mass parameter or 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 \cite{27,29} where symmetry breaking occurred at TeV scale leading to right-handed charged gauge boson $W_R$ and right handed neutrino $N_R$ mass in order of TeV scale. This leads to new physics contribution to $0\nu\beta\beta$ due to right handed current via $W_R - W^\nu_R$ mediation and heavy neutrino exchange.

When we considered LRSM with type II see saw dominance, the mass eigenvalues of the left and right handed neutrinos are proportional to each other, 
\[ m_L \propto M_R \]  
(7)

As a result of this, the left and right handed neutrinos have the same PMNS mixing matrix,
\[ U_L^{PMNS} = U_R^{PMNS} \]  
(8)

and the mass eigenvalues are related as follows:

**Normal Ordering (NO)** ($m_1 = m_{\text{lightest}}$)
\[ m_2 = \sqrt{m_1^2 + \Delta m^2_{sol}}; \quad m_3 = \sqrt{m_1^2 + \Delta m^2_{sol} + \Delta m^2_{atm}}. \]  
(9)

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

**Inverted Ordering (IO)** ($m_3 = m_{\text{lightest}}$)
\[ m_1 = \sqrt{m_3^2 + \Delta m^2_{atm}}; \quad m_2 = \sqrt{m_3^2 + \Delta m^2_{atm} + \Delta m^2_{sol}}. \]  
(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 in to consideration, the inverse half life of a given isotope for $0\nu\beta\beta$ is given by
\[ t_{1/2}\text{[LR]}^{-1} = G \left| \frac{M_{W_R}}{m_e} \right|^2 \left( |m_{ee}^\nu|^2 + |m_{ee}^N|^2 \right) \]  
(11)

\[ = G \left| \frac{M_{W_R}}{m_e} \right|^2 |m_{ee}^\nu|^2 \]  
(11)

III. 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 exchange of light Majorana neutrinos discussed in previous section light or by corresponding new interactions.

![Diagram](https://via.placeholder.com/150)

FIG. 1: Effective majorana mass $m_{ee}^\nu$ for neutrinoless double beta decay as a function of lightest neutrino mass for standard mechanism. Here the red and green band are correspond to the solution of $\theta_{12}$ and $\theta_{13}$ for NO, blue and magenta band are correspond to the solution of $\theta_{12}$ and $\theta_{13}$ for IO.

From the Fig[1] for NO, we found out that $m_{ee}^\nu$ for the DLMA solution is shifted in to the region between the NO and IO for LMA solution which is called as desert region and $m_{ee}^\nu$ for the DLMA solution is found out to be higher than that of LMA solution and when the $m_{\text{lightest}}$ increases, the overlap region between the LMA and DLMA solution is also increases. For $m_{\text{lightest}} \in [10^{-3}, 10^{-2}]$eV, we found the minimum value of $m_{ee}^\nu$ for LMA solution is very small i.e nearly vanishes but for DLMA solution, in that region minimum value of $m_{ee}^\nu$ remain same as the value when $m_{\text{lightest}} < 10^{-3}$eV for NO.

But in case of IO, maximum value of $m_{ee}^\nu$ for both LMA and DLMA solution remain same where as the minimum value of $m_{ee}^\nu$ for DLMA solution is slightly higher than the LMA solution which is nearly same. The overlap region between LMA and DLMA solution remain same through out the value of $m_{\text{lightest}}$. Here The DLMA solution fully overlap the LMA solution. There is no considerable change found out between the both of these solution for IO. So the $m_{ee}^\nu$ remain same for both LMA and DLMA solution in IO.
where $m_{ee}^\nu$ is the effective mass arises due to left handed neutrino in standard mechanism and $m_{ee}^N$ is the effective mass arises due to purely right handed current. and here $|m_{ee}^{N}|^2 = |m_{ee}^{LR}|^2 = |m_{ee}^{LR}|^2 + |m_{ee}^{N}|^2$ where $m_{ee}^{LR}$ is the total effective mass arises due to right handed current in LRSM.

We know the expression for $m_{ee}^\nu$ that is given in eq(4) and the expressions for $m_{ee}^N$ is given by

\[
m_{ee}^N = \frac{C_N}{M_3} \left| a_1^2 + a_2^2 a_3^2 \right| (m_1^2 + m_2^2 + m_3^2) \]  \hspace{1cm} (NO) \\
= \frac{C_N}{M_2} \left| a_1^2 + a_2^2 a_3^2 \right| (m_1^2 + m_2^2 + m_3^2) \]  \hspace{1cm} (IO)
\]

where $C_N = (\langle p^2$n $\rangle) \left( \frac{a_n}{a_n} \right)$. Here typical momentum transfer $\langle p \rangle \approx 100$ MeV, $g_R$ and $g_L$ are the coupling constant of SU$(2)_L$ & SU$(2)_R$ respectively and $M_W$ is the mass of the left and right handed gauge boson i.e $W_L$ and $W_R$ respectively that mediate the process. In this paper, we denote $M_3$ 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 $M_{WW} \approx 35$ TeV. By varying all the oscillation parameter in their $3\sigma$ range, 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 out that the effective mass($m_{ee}^{LR}$) remain nearly same for higher value of absolute mass i.e $m_{lightest} > 0.03$ eV, but that region is disfavoured by the cosmological constraint. We observed that both of the LMA and DLMA solution for NO saturate the higher value of effective mass limit provided by KamLAND-Zen and GERDA, so that we can find the lower limit of absolute mass of the lightest neutrino. Here the DLMA solution (Green band) is shifted towards the left as comparing with the LMA solution (Red band) that leading to 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 same for both of these solution for NO. So the lower limit of absolute mass of the lightest neutrino for NO is found out to be

\[
m_{lightest} > 5.01 \times 10^{-4} \text{ (for LMA solution)} \\
m_{lightest} > 2.15 \times 10^{-4} \text{ (for DLMA solution)}
\]

In case of IO, $m_{ee}^{LR}$ remain same for both LMA and DLMA solution. So both of these solution are equal for IO. Here also both of these solution saturate the higher value of $m_{ee}^{LR}$. As both LMA and DLMA solution for NO saturate the experimental limit provided by KamLAND-Zen and GERDA, so that we can find the lower limit of absolute mass of the lightest neutrino for both of the LMA and DLMA solution for NO.

IV. CONCLUSION

If the $0\nu\beta\beta$ process happens, it will adresses many unsolved fundamental question of physics like majorana nature of neutrino, matter antimatter asymmetry, absolute mass scale and mass ordering of neutrino that help us for the better understanding of the universe. So searching for this rare process are of paramount importance. From the standard mechanism, we found out that the DLMA solution for NO is shifted in to the desert region($0.004 - 0.0075$ eV) which provide a new sensitivity goal for future experiment. If we find out 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 out that both LMA and DLMA solution 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 does not provide by standard mechanism. So if we find out any positive signal for $0\nu\beta\beta$ above the region of IO in standard mechanism, we have to consider the contribution from the right handed current.

\[
\text{DISALLOWED REGION} \\
\text{KamLAND-Zen + GERDA} \\
\text{IO} \\
\text{NO} \\
\text{Planck}
\]

\begin{center}
\begin{tabular}{|c|c|c|}
\hline
$m_{ee}$ [eV] & $m_{LR}$ [eV] & $m_{mee}$ [eV] \\
\hline
0.001 & 0.005 & 0.010 \\
0.050 & 0.100 & 0.500 \\
1 & 10 & 100 \\
\hline
\end{tabular}
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