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Constraining Neutrino Mass from Neutrinoless Double Beta Decay

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We re-analyze the compatibility of the claimed observation of neutrinoless double beta decay ($0\nu\beta\beta$) in ^{76}Ge with the new limits on the half-life of ^{136}Xe from EXO-200 and KamLAND-Zen. Including recent calculations of the nuclear matrix elements (NMEs), we show that while the claim in ^{76}Ge is still compatible with the individual limits from ^{136}Xe for a few NME calculations, it is inconsistent with the KamLAND-Zen+EXO-200 combined limit for all but one NME. After imposing the most stringent upper limit on the sum of light neutrino masses from Planck, we find that the canonical light neutrino contribution cannot satisfy the claimed $0\nu\beta\beta$ signature or saturate the current limit, irrespective of the NME uncertainties. However, inclusion of the heavy neutrino contributions, arising naturally in TeV-scale Left-Right symmetric models, can saturate the current limit of $0\nu\beta\beta$. In a type-II seesaw framework, this imposes a lower limit on the lightest neutrino mass. Depending on the mass hierarchy, we obtain this limit to be in the range of 0.07 - 4 meV for a typical choice of the right-handed (RH) gauge boson and RH neutrino masses relevant for their collider searches. Using the $0\nu\beta\beta$ bounds, we also derive correlated constraints in the RH sector, complimentary to those from the LHC.

Introduction – The discovery of neutrino oscillations, and hence, non-zero neutrino masses and mixing implies physics beyond the Standard Model (SM). Some of the unresolved issues are (i) whether neutrinos are Majorana or Dirac particles, (ii) their absolute mass scale, and (iii) their mass hierarchy. Neutrinoless double beta decay ($0\nu\beta\beta$) [1], if observed, would imply lepton number violation (LNV) and Majorana nature of neutrinos [2], and could possibly shed light on the other issues.

Experimental studies of the $0\nu\beta\beta$ process: $(A,Z) \to (A,Z+2)+2e^-$ have been conducted on several nuclei, and to date, there has been only one claimed observation in ^{76}Ge with half-life $T^{0\nu}_{1/2}(^{76}\text{Ge}) = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr at 68% CL [3]. Several ongoing experiments have design sensitivities to test this claim. Recently, the KamLAND-Zen (KLZ) experiment using ^{136}Xe obtained the limit $T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.9 \times 10^{25}$ yr at 90% CL [4]. After combining with the EXO-200 (EXO) results, $T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.6 \times 10^{25}$ yr [5], they derived the limit $T^{0\nu}_{1/2}(^{136}\text{Xe}) > 3.4 \times 10^{25}$ yr at 90% CL [4], and disfavored the claim in [3] at $> 97.5\%$ CL, using recent calculations of the nuclear matrix elements (NMEs).

On the other hand, the Planck results in conjunction with other cosmological data have put a stringent upper limit on the sum of light neutrino masses: $\sum m_\nu < 0.23$ eV at 95% CL [6], which rules out most of the quasi-degenerate region of the light neutrino mass spectrum. This has important consequences for the canonical interpretation of $0\nu\beta\beta$ via light neutrino exchange [7].

In this paper we study the implications of these recent results on various aspects of the $0\nu\beta\beta$ phenomenology, namely, we (i) re-analyze the compatibility of the KamLAND-Zen and EXO-200 limits with the claimed observation [3], including the uncertainties due to several updated NME calculations; (ii) quantify whether the standard light neutrino prediction for $0\nu\beta\beta$ can satisfy the claimed observation or saturate the current limit, while being consistent with the stringent neutrino mass constraints from cosmology; and (iii) investigate whether a heavy neutrino contribution naturally arising in low scale Left-Right symmetric models (LRSM), accessible at the LHC, can saturate the $0\nu\beta\beta$ limit.

Light Neutrino Contribution– For $0\nu\beta\beta$ mediated by the light Majorana neutrinos, the half-life is given by

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{ee}}{m_e}\right|^2 , \qquad (1)$$

where $G_{0\nu}$, $\mathcal{M}_\nu$ and m_e are the the phase space factor, the NME, and the electron mass respectively. Here $m^\nu_{ee} = \sum_i U^2_{ei} m_i$ is the effective mass, where U is the PMNS mixing matrix diagonalizing the light neutrino mass matrix with eigenvalues m_i $(i = 1,2,3)$. Using the standard parametrization for U, we obtain (with $c_{ij} \equiv \cos\theta_{ij}, s_{ij} \equiv \sin\theta_{ij}$)

$$m^\nu_{ee} = m_1 c^2_{12} c^2_{13} + m_2 s^2_{12} c^2_{13} e^{2i\alpha_2} + m_3 s^2_{13} e^{2i\alpha_3} . \qquad (2)$$

To test the compatibility between the claim in [3] and the null results in [4, 5], it is useful to study the correlation between their half-lives (see also [8]) using Eq. (1):

$$T^{0\nu}_{1/2}(^{136}\text{Xe}) = \left(3.61^{+1.18}_{-0.83} \times 10^{24}\ \text{yr}\right) \left|\frac{\mathcal{M}_{0\nu}(^{76}\text{Ge})}{\mathcal{M}_{0\nu}(^{136}\text{Xe})}\right|^2 (3)$$

where we have used the recently re-evaluated phase space factors [9] for the axial-vector coupling constant $g_A =$

1.25. We take the claimed value for $T_{1/2}^{0\nu}(^{76}\mathrm{Ge})$ [3] at 90% CL (assuming Gaussian errors). An experimental limit on $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ larger than the predicted value from Eq. (3) will rule out the positive claim of [3]. Using various updated NME calculations [10–16], we show in Table I the predicted range of $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ at 90% CL. Note that for a given NME method, when different versions of the results are available, we only quote the extreme (smallest and largest) values to show the allowed ranges. We find that it is still compatible with the individual limits from KLZ and EXO for some of the NMEs calculated by QRPA method [14–16], but inconsistent with their combined limit in [4] for all of the NME values, except the one given in [16]. The reason is the very small NME for ^{136}Xe in [16], which can be attributed to the differences in pairing structure in the neutron mean fields, thus leading to a small overlap in the initial and final mean fields.

NME			$T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$
Method	$\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})$	$\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})$	[10^{25} yr]
EDF(U) [10]	4.60	4.20	0.33 - 0.57
ISM(U) [11]	2.81	2.19	0.46 - 0.79
IBM-2 [12]	5.42	3.33	0.74 - 1.27
pnQRPA(U) [13]	5.18	3.16	0.75 - 1.29
SRQRPA-B [14]	5.82	3.36	0.84 - 1.44
SRQRPA-A [14]	4.75	2.29	1.20 - 2.06
QRPA-B [15]	5.57	2.46	1.43 - 2.46
QRPA-A [15]	5.16	2.18	1.56 - 2.69
SkM-HFB-QRPA [16]	5.09	1.89	2.02 - 3.47

TABLE I. Predictions for $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ at 90% CL corresponding to the claimed $0\nu\beta\beta$ observation in ^{76}Ge [3] for the latest results of different NME calculations [10–16].

For comparison of the experimental results with the canonical light neutrino contribution given by Eq. (1) including all the NME uncertainties, it is better to consider the individual half-lives of different isotopes (instead of the effective mass which is theoretically independent of the NME uncertainties). Hence, we show in Fig. 1 the predicted half-lives for ^{76}Ge and ^{136}Xe as a function of the lightest neutrino mass for normal and inverted mass orderings, including the hierarchical and quasi-degenerate (QD) regimes. We have varied the oscillation parameters in their 3σ range [17], the *CP* phases from 0 to π, and included the NME uncertainties from Table I (light shaded regions). Note that the predicted regions of half-life for normal hierarchy (NH) and inverted hierarchy (IH) almost overlap due to the NME uncertainties. However, for a given set of NMEs (e.g., those of [14] taken here for illustration), we recover the standard picture with the two (dark shaded) regions well-separated. The green (solid) horizontal lines in the left panel of Fig. 1 correspond to the 90% CL claim value of [3] (KK), and the brown (dashed) horizontal line for the lower limit set by the Heidelberg-Moscow collaboration [18] (HM). The orange (solid) and brown (dashed) horizontal lines in the right panel represent the 90% CL lower limits for ^{136}Xe from KLZ and combined KLZ+EXO [4] respectively. The solid vertical line shows the 95% CL limit, $\sum m_\nu < 0.23$ eV (Planck1), derived from the Planck+WMAP low-multipole polarization+high resolution CMB+baryon acoustic oscillation (BAO) data and assuming a standard ΛCDM model of cosmology, whereas the dashed vertical line shows the limit without the BAO data set: $\sum m_\nu < 0.66$ eV (Planck2) [6]. Note that although the cosmological bound on the sum of neutrino masses depends strongly on the choice of data sets, it is currently stronger than the direct experimental bound coming from Tritium β decay experiment: $m_{\nu_e} \lesssim 2$ eV [19].

The current constraints on $0\nu\beta\beta$ (including the claim) can be saturated by the canonical contribution only in the QD regime with $m_1 \simeq m_2 \simeq m_3 \equiv m_0 \gtrsim 0.1$ eV. As it is evident from Fig. 1, this possibility is excluded, regardless of the NME uncertainties, if we take the most stringent upper limit from cosmology which for QD neutrinos gives $m_0 < 0.077$ eV. For other cosmological data sets, only a very narrow allowed mass window remains.

Heavy Neutrino Contribution– The heavy right-handed (RH) neutrinos, introduced in the type-I seesaw [20] models, if sufficiently light ($\leq 10\,\mathrm{TeV}$), can give a significant contribution to $0\nu\beta\beta$ [21] provided their mixing with the active neutrinos is sizeable. However, this requires fine-tuning and/or cancellation [22]. A more natural way to obtain appreciable heavy neutrino contributions to the $0\nu\beta\beta$ amplitude arises in the TeV scale LRSM [23] via RH currents [24, 25]. Such models also lead to other high and low-energy phenomena and could for instance be directly probed at the LHC through the same-sign dilepton signal [26].

The LRSM includes heavy neutrinos as part of the $SU(2)_R$ doublet and restores parity at high energies [23]. This naturally leads to small neutrino masses through either type-I seesaw via the RH neutrinos [20] or type-II seesaw via $SU(2)$ triplet scalars [27] or both [28]. The corresponding Lagrangian is given by

$$\mathcal{L}_Y = f_\nu \bar{L}_L \Phi L_R + \widetilde{f}_\nu \bar{L}_L \widetilde{\Phi} L_R + f_L L_L^\mathsf{T} C i\sigma_2 \Delta_L L_L + f_R L_R^\mathsf{T} C i\sigma_2 \Delta_R L_R + \mathrm{h.c.} \tag{4}$$

Here C is the charge conjugation operator and σ_2 the second Pauli Matrix, $L_{L(R)}$ denotes the lepton doublet, Φ the SM Higgs doublet, $\widetilde{\Phi} = \sigma_2\Phi^*\sigma_2$, and $\Delta_{L(R)}$ the scalar triplet belonging to $SU(2)_{L(R)}$. The light neutrino mass matrix in the seesaw approximation is $M_\nu \simeq m_L - m_D^\mathsf{T} M_R^{-1} m_D$, where $m_D = f_\nu v$, $m_L = f_L v_L$, $M_R = f_R v_R$, and v, $v_{L(R)}$ are the vacuum expectation values of doublet and triplet Higgs fields: $\langle\Phi\rangle =$

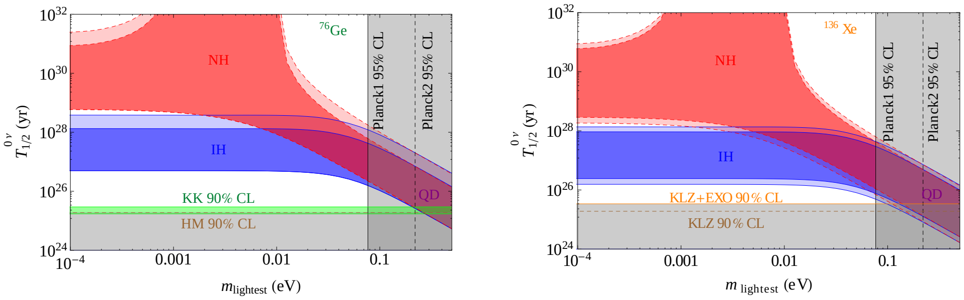

FIG. 1. The predicted half-life of $0\nu\beta\beta$ in ^{76}Ge (left) and ^{136}Xe (right) due to light neutrino exchange. The light shaded regions include the uncertainties due to all the NMEs listed in Table I, whereas the dark shaded regions correspond to the NMEs in [14]. The grey regions are excluded from $0\nu\beta\beta$ and Planck results (see text for details).

v, $\langle\Delta_{L(R)}\rangle = v_{L(R)}$. The heavy neutrino masses $\sim M_R$ are related to the RH gauge boson mass $M_{W_R} = g v_R$.

There are several diagrams leading to double beta decay in LRSM (see [1] and references therein). In this work we consider the appealing case of type-II dominance [24]. Also, the scalar triplet contribution is expected to be small due to constraints from lepton flavor violation, which typically require $M_N/M_\Delta \lesssim 0.1$ [24]. Hence, we focus only on the diagram with purely RH currents, mediated by the heavy neutrinos which adds coherently to the purely left-handed light neutrino contribution discussed earlier:

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m_{ee}^{(\nu+N)}}{m_e}\right|^2 , \tag{5}$$

where $\left|m_{ee}^{(\nu+N)}\right|^2 = |m_{ee}^\nu|^2 + |m_{ee}^N|^2$, with m_{ee}^ν given by Eq. (2) and m_{ee}^N is the heavy neutrino effective mass:

$$m_{ee}^N = \langle p^2\rangle \frac{M_{W_L}^4}{M_{W_R}^4} \sum_j \frac{V_{ej}^2}{M_j} . \tag{6}$$

Here $\langle p^2\rangle = -m_e m_p \mathcal{M}_N/\mathcal{M}_\nu$ denotes the virtuality of the exchanged neutrino, m_p is the mass of the proton and $\mathcal{M}_N$ is the NME corresponding to the RH neutrino exchange. Note that Eq. (6) is valid only in the heavy neutrino limit: $M_j^2 \gg |\langle p^2\rangle|$ which is assumed hereafter. Using the values for $\mathcal{M}_\nu$ and $\mathcal{M}_N$ from [14], we get $\langle p^2\rangle = -(157$ - $185\ \text{MeV})^2$ for ^{136}Xe and $-(153$ - $184\ \text{MeV})^2$ for ^{76}Ge. The unitary matrix V in Eq. (6) diagonalizes M_R with mass eigenvalues M_j. We further assume the discrete LR symmetry to be parity, under which $f_L = f_R$ and $U = V$. Our conclusions remain unchanged for the other possibility viz. charge conjugation: $f_L = f_R^*$ and $U = V^*$.

In the type-II limit, $M_\nu \simeq m_L = (v_L/v_R)M_R$ and $m_i \propto M_i$. Hence, for the normal ordering we have $M_1 < M_2 \ll M_3$ as well, and the RH neutrino masses can be expressed in terms of the heaviest one as $M_1/M_3 = m_1/m_3,\ M_2/M_3 = m_2/m_3$. Then

$$m_{ee}^N|_{\rm nor} = \frac{C_N}{M_3}\left(\frac{m_3}{m_1}c_{12}^2c_{13}^2 + \frac{m_3}{m_2}s_{12}^2c_{13}^2e^{2i\alpha_2} + s_{13}^2e^{2i\alpha_3}\right),$$

where $C_N = \langle p^2\rangle M_{W_L}^4/M_{W_R}^4$. For inverted ordering, M_2 will be the largest, and hence

$$m_{ee}^N|_{\rm inv} = \frac{C_N}{M_2}\left(\frac{m_2}{m_1}c_{12}^2c_{13}^2 + s_{12}^2c_{13}^2e^{2i\alpha_2} + \frac{m_2}{m_3}s_{13}^2e^{2i\alpha_3}\right).$$

In Fig. 2, we show the half-life predictions for ^{76}Ge and ^{136}Xe using Eq. (5), and including the light and heavy neutrino NME ranges given in [14] (corresponding to $g_A = 1.25$). Here we have chosen $M_{W_R} = 3$ TeV and the heaviest neutrino mass, $M_{N_>} = 1$ TeV, keeping in mind the current LHC exclusion limits [29] and its future accessible range. Note that for this choice of $M_{N_>}$, and for the range of the lightest neutrino mass shown in Fig. 2, the lightest RH neutrino mass is $M_{N_<} > 490$ MeV, which justifies the validity of Eq. (6). Several important conclusions can be drawn from this illustrative plot: (i) the purely RH contribution via exchange of heavy neutrinos, when added to the standard light neutrino contribution, can saturate the current experimental limit (or satisfy the claim) even for hierarchical neutrinos; (ii) for the heavy neutrino contribution saturating the bound on $T^{0\nu}_{1/2}$, there exists an absolute *lower* bound on the lightest neutrino mass both for orderings: (2 - 4) meV for NH and (0.07 - 0.2) meV for IH. The range is due to the combined effect of the NME uncertainties and the 3σ range of the oscillation parameters used here. Needless to mention, the lower bound will become stronger with improved experimental bounds on $0\nu\beta\beta$ in future. (iii) the KK claim can be reached for the lightest neutrino mass in the range of (1 - 3) meV for NH and (0.03 - 0.1) meV for IH. These values are well within the most stringent Planck limit of 77 meV; (iv) for the heavy neutrino contribution, the compatibility between the KK claim and KLZ+EXO bound can be examined using Eq. (3), with the NMEs for light neutrinos replaced by those for heavy neutrinos [14]. It predicts the half-life for ^{136}Xe in the

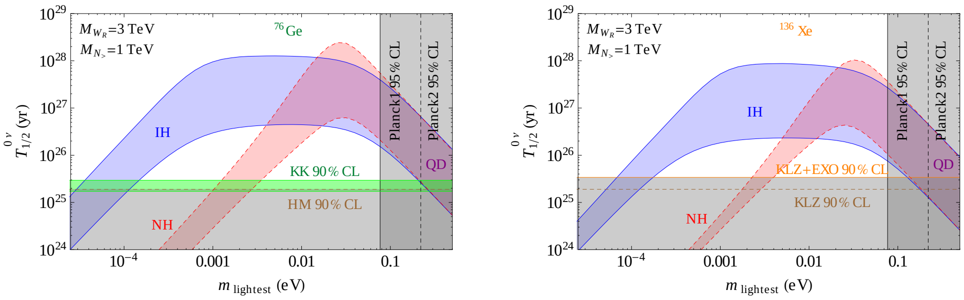

FIG. 2. The light+heavy neutrino contribution to the $0\nu\beta\beta$ half-life of ^{76}Ge (left) and ^{136}Xe (right) for both NH and IH, and with type-II seesaw dominance. Here $(M_{W_R}, M_{N_>}) = (3,1)$ TeV. The vertical and horizontal lines are same as in Fig. 1.

range $(0.56-2.74)\times 10^{25}$ yr at 90% CL, for all the corresponding NMEs in [14]. Thus in this case also, the KK claim is compatible with the individual KLZ and EXO bounds, but inconsistent with their combined limit. Similar conclusion holds for the light+heavy neutrino contribution, since the KK claim can be saturated while being consistent with cosmology only by a dominant heavy neutrino contribution; (v) the lower bound is sensitive to the RH neutrino and gauge boson masses. For a given W_R mass, the lower bound on m_{lightest} is weakened by increasing the RH neutrino mass $M_{N>}$, and the bound tightens for lower $M_{N>}$ (as long as we are in the heavy neutrino regime so that Eq. (6) is valid; otherwise, no lower limit on m_{lightest} can be derived). The trend is similar if we vary the W_R mass, but more pronounced due to the $M_{W_R}^{-4}$ dependence in Eq. (6).

Complementarity with the LHC results – $0\nu\beta\beta$ provides a complementary probe to collider searches for LNV. The correlation between the heavy gauge boson mass and the lightest RH neutrino mass for a TeV-scale LRSM is shown in Fig. 3 for both mass orderings. In the brown (dashed) shaded region, the half-life in Eq. (5) saturates the combined limit from KLZ+EXO [4], whereas the region to its left (right) is excluded (allowed) by this limit. The width of the brown region is due to the variation of the oscillation parameters in their 3σ range [17] and the lightest neutrino mass up to the most stringent upper limit from Planck. We have considered the NMEs for ^{136}Xe corresponding to light and heavy neutrino exchange [14] which yield the smallest $|\langle p^2\rangle|$, and hence, the strongest limit in Fig. 3. The current LHC exclusion regions [29] are also shown for comparison (see also [30] for detail discussion on collider searches). We find that (i) for the normal ordering, a part of the parameter space not accessible at the LHC can be constrained (or probed in case of an observation) through $0\nu\beta\beta$, and (ii) for the inverted ordering, it is not possible to exclude any parameter space in the $M_{W_R} - M_{N_<}$ plane from $0\nu\beta\beta$ due to cancellations in m_{ee}^N.

Conclusion– In summary, (i) the positive claim of $0\nu\beta\beta$ in ^{76}Ge is still compatible with the individual ^{136}Xe limits from EXO-200 and KamLAND-Zen due to NME uncertainties, whereas the combined limit excludes this for all but one NME calculations; (ii) the most stringent limit on $\sum m_\nu$ from Planck, in conjunction with the KamLAND-Zen+EXO-200 bound, excludes the possibility of saturating the limit for ^{136}Xe or the claim in ^{76}Ge solely by the canonical light neutrino contribution; (iii) the additional heavy neutrino contribution to $0\nu\beta\beta$ via purely RH currents in the TeV-scale minimal Left-Right extension of the SM can saturate the current experimental bound. For type-II seesaw dominance, it sets a lower limit on the lightest neutrino mass; (iv) we show for normal mass ordering, $0\nu\beta\beta$ puts additional constraints in the RH gauge boson and heavy neutrino mass plane, complementary to those from LHC.

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Note Added– After submission of our paper, new results were announced from phase I of GERDA experiment [31], which set new limits on $0\nu\beta\beta$ half-life of ^{76}Ge: $T^{0\nu}_{1/2}(^{76}\text{Ge}) > 2.1\times 10^{25}$ yr at 90% CL, and when combined with other Ge-based experiments, namely, HM [18] and IGEX [32], it becomes $T^{0\nu}_{1/2}(^{76}\text{Ge}) > 3.0\times 10^{25}$ yr at 90% CL. This new result disfavors the KK claim [3] independent of NME and of the physical mechanism for $0\nu\beta\beta$. In view of these new results, we show the updated Figs. 1 and 2 for ^{76}Ge in Fig. 4. Our conclusion remains unchanged that the canonical light neutrino contribution by itself cannot saturate the GERDA+HM+IGEX limit, irrespective of the NME uncertainties. After taking into account the new contributions from a TeV-scale LR model with Type-II seesaw, this limit can be saturated. However it puts a lower limit on the lightest neutrino mass in the range of (2-4) meV for NH and (0.03-0.2)

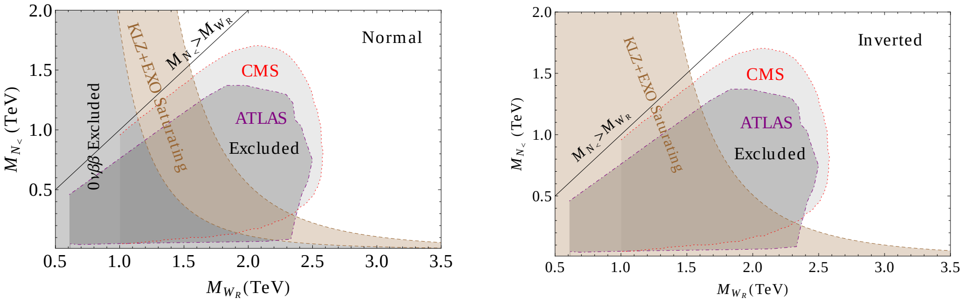

FIG. 3. The $0\nu\beta\beta$ constraints in the M_{W_R}-$M_{N_<}$ plane, along with the direct search limits from CMS and ATLAS. The brown (dashed) region saturates the KLZ+EXO combined limit, and the grey (white) region is excluded (allowed).

meV for IH in the context of this model.

For completeness, we also compare the corresponding upper limits on the effective neutrino mass using the recent results for ^{76}Ge and ^{136}Xe. For all the NMEs given in Table I, our results for the effective neutrino mass due to canonical light neutrino contribution are given in Table II. For comparison, we also give the corresponding ranges preferred by the claimed observation in [3]. It is again clear, as in Table I, that the KK claim, while compatible with the individual limits from KLZ for some of the QRPA NMEs in [14–16], is inconsistent with the combined (KLZ+EXO) limit for all NMEs, except [16]. Also we find that the limits on m_{ee}^{ν} derived from ^{136}Xe are stronger than those from ^{76}Ge for all the NMEs, except [16] in which case the two limits are similar.

NME	Limit on m_{ee}^{ν} (eV)				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
EDF(U) [10]	0.32	0.27	0.27-0.35	0.15	0.11
ISM(U) [11]	0.52	0.44	0.44-0.58	0.28	0.21
IBM-2 [12]	0.27	0.23	0.23-0.30	0.19	0.14
pnQRPA(U) [13]	0.28	0.24	0.24-0.31	0.20	0.15
SRQRPA-B [14]	0.25	0.21	0.21-0.28	0.18	0.14
SRQRPA-A [14]	0.31	0.26	0.26-0.34	0.27	0.20
QRPA-B [15]	0.26	0.22	0.22-0.29	0.25	0.19
QRPA-A [15]	0.28	0.24	0.24-0.31	0.29	0.21
SkM-HFB-QRPA [16]	0.29	0.24	0.24-0.32	0.33	0.25

TABLE II. The upper limits on the effective neutrino mass m_{ee}^{ν} corresponding to the 90% CL lower bounds on half-lives of ^{76}Ge (from GERDA and GERDA+HM+IGEX combined [31]) and ^{136}Xe (from KLZ and KLZ+EXO combined [4]) for different NME calculations [10–16]. Also shown are its preferred ranges corresponding to the 90% CL half-life of ^{76}Ge from the KK claim [3].

Similarly, for the heavy neutrino contribution in our minimal LR model, we can derive an upper limit on the quantity $M_{W_R}^{-4}\sum_j V_{ej}^2/M_j$ given in Eq. (6) using the experimental lower limits on $T_{1/2}^{0\nu}$. Our results are given in Table III for the NMEs in [14]. Here "Argonne" and "CD-Bonn" stand for different nucleon-nucleon potentials, and "large" or "intm" refer to different size of the single-particle spaces in the model. From Table III we see that even with the heavy neutrino contribution, the incompatibility between the KK claim and the recent combined limits from ^{76}Ge and ^{136}Xe experiments still persists. Moreover, the limits from ^{136}Xe on the parameter characterizing the heavy neutrino contribution to $0\nu2\beta$ are found to be stronger than those from ^{76}Ge.

SRQRPA NME method	Limit on $M_{W_R}^{-4}\sum_j V_{ej}^2/M_j$ (TeV^{-5})				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
Argonne intm	0.30	0.24	0.24-0.33	0.18	0.13
Argonne large	0.26	0.22	0.22-0.29	0.18	0.14
CD-Bonn intm	0.20	0.16	0.17-0.22	0.17	0.13
CD-Bonn large	0.17	0.14	0.14-0.18	0.17	0.13

TABLE III. The upper limits on the heavy neutrino effective mass parameter $M_{W_R}^{-4}\sum_j V_{ej}^2/M_j$ corresponding to the 90% CL lower bounds on half-lives of ^{76}Ge (from GERDA and GERDA+HM+IGEX combined [31]) and ^{136}Xe (from KLZ and KLZ+EXO combined [4]) for the heavy neutrino NMEs in [14]. Also shown are its preferred ranges corresponding to the 90% CL half-life of ^{76}Ge from the KK claim [3].

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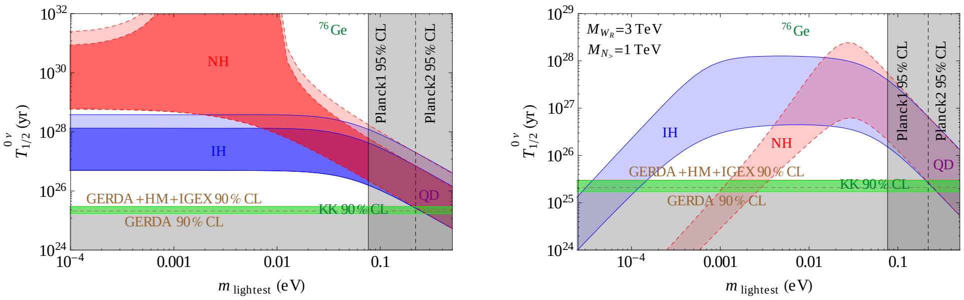

FIG. 4. The updated Fig. 1 (left panel) and Fig. 2 (right panel) for ^{76}Ge after including the recent GERDA phase I results.

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