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Constraining neutrino mass from neutrinoless double beta decay

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We study the implications of the recent results on neutrinoless double beta decay ($0\nu\beta\beta$) from GERDA-I (^{76}Ge) and KamLAND-Zen + EXO-200 (^{136}Xe) and the upper limit on the sum of light neutrino masses from Planck. We show that the upper limits on the effective neutrino mass from ^{136}Xe are stronger than those from ^{76}Ge for most of the recent calculations of the nuclear matrix elements (NMEs). We also analyze the compatibility of these limits with the claimed observation in ^{76}Ge and show that while the updated claim value is still compatible with the recent GERDA limit as well as the individual ^{136}Xe limits for a few NME calculations, it is inconsistent with the combined ^{136}Xe limit for all but one NME. Imposing the most stringent limit from Planck, we find that the canonical light neutrino contribution cannot saturate the current limit, irrespective of the NME uncertainties. Saturation can be reached by inclusion of the right-handed (RH) neutrino contributions in TeV-scale left-right symmetric models with type-II seesaw. This imposes a lower limit on the lightest neutrino mass. Using the $0\nu\beta\beta$ bounds, we also derive correlated constraints in the RH sector, complimentary to those from direct searches at the LHC.

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I. INTRODUCTION

The observation of neutrino oscillations implies nonzero neutrino masses and mixing. Some of the yet 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 ($0\nu\beta\beta$): $(A, Z) \to (A, Z+2) + 2e^-$ [1], if observed, would imply lepton number violation (LNV) and Majorana nature of neutrinos [2], and could possibly shed light on the other issues.

To date, there has been only one claimed observation of $0\nu\beta\beta$ in ^{76}Ge with half-life $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = (1.19^{+0.37}_{-0.23}) \times 10^{25}$ yr [3], which was later updated to $(2.23^{+0.44}_{-0.31}) \times 10^{25}$ yr at 68% C.L. (KK) [4] using pulse shape information. Several ongoing experiments have design sensitivities to test this claim. Recently, the KamLAND-Zen (KLZ) experiment using ^{136}Xe obtained the limit $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.9 \times 10^{25}$ yr at 90% C.L. [5]. Using the earlier EXO-200 (EXO) result, $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.6 \times 10^{25}$ yr [6], they derived the combined limit $T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 3.4 \times 10^{25}$ yr at 90% C.L. [5] and disfavored the KK claim at >97.5% C.L. using the correlation between ^{76}Ge and ^{136}Xe results. Recently, GERDA-I has reported a new limit on $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 2.1 \times 10^{25}$ yr [7] at 90% C.L., which when combined with the Heidelberg-Moscow (HM) [8] and IGEX [9] data gives $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}$ yr at 90% C.L. [7]. Note that while GERDA-I limit rules out the previous positive claim [3], it does *not* rule out the updated KK result [4]. Hence, it is important to study the correlation between ^{76}Ge and ^{136}Xe limits to have a complementary test of the KK claim.

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% C.L. [10], which rules out most of the quasidegenerate region of the light neutrino mass spectrum [11]. This has important consequences for the canonical interpretation of $0\nu\beta\beta$ [12].

In this paper we study various implications of these recent results, namely, we (i) study the correlation between the ^{76}Ge and ^{136}Xe results using several updated nuclear matrix element (NME) calculations and compare the corresponding upper limits on the effective neutrino mass, (ii) analyze the compatibility of the current KLZ limit with the KK claim, including the NME uncertainties, and also analyze the future compatibility of the projected ^{76}Ge and ^{136}Xe half-lives, (iii) quantify whether the standard light neutrino prediction for $0\nu\beta\beta$ can satisfy the KK claim or saturate the current limit, while being consistent with the stringent constraints from cosmology, and (iv) investigate whether a heavy neutrino contribution, naturally arising in TeV-scale left-right symmetric models (LRSM), can saturate the $0\nu\beta\beta$ limit.

II. LIGHT NEUTRINO CONTRIBUTION

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

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

TABLE I. Upper limits on the effective neutrino mass m_{ee}^{ν} corresponding to the 90% C.L. lower bounds on half-lives of ^{76}Ge (from GERDA and GERDA + HM + IGEX combined [7]) and ^{136}Xe (from KLZ and KLZ + EXO combined [5]), along with its 90% C.L. range preferred by the KK claim [4], derived using the latest results of different NME calculations [13–19]. Also shown are the $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ values corresponding to the KK claim in ^{76}Ge [4] at 90% C.L., derived using the correlation Eq. (2); the corresponding $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ values for the earlier KK claim [3] are roughly a factor of 2 smaller than the values shown here.

NME			90% C.L. upper limit on m_{ee}^{ν} (eV)					90% C.L.
Calculation method	$\mathcal{M}_\nu$		^{76}Ge			^{136}Xe		KK compatible
	^{76}Ge	^{136}Xe	GERDA	Comb	KK Claim	KLZ	Comb	$T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ [10^{25} yr]
EDF(U) [13]	4.60	4.20	0.32	0.27	0.27–0.35	0.15	0.11	0.33–0.57
ISM(U) [14]	2.81	2.19	0.52	0.44	0.44–0.58	0.28	0.21	0.46–0.79
IBM-2 [15]	5.42	3.33	0.27	0.23	0.23–0.30	0.19	0.14	0.74–1.27
pnQRPA(U) [16]	5.18	3.16	0.28	0.24	0.24–0.31	0.20	0.15	0.75–1.29
SRQRPA-B [17]	5.82	3.36	0.25	0.21	0.21–0.28	0.18	0.14	0.84–1.44
SRQRPA-A [17]	4.75	2.29	0.31	0.26	0.26–0.34	0.27	0.20	1.20–2.06
QRPA-B [18]	5.57	2.46	0.26	0.22	0.22–0.29	0.25	0.19	1.43–2.46
QRPA-A [18]	5.16	2.18	0.28	0.24	0.24–0.31	0.29	0.21	1.56–2.69
SkM-HFB-QRPA [19]	5.09	1.89	0.29	0.24	0.24–0.32	0.33	0.25	2.02–3.47

where $G_{0\nu}$, $\mathcal{M}_\nu$ and m_e are the phase space factor, the NME, and the electron mass, respectively. Here $m_{ee}^{\nu} = \sum_i U_{ei}^2 m_i$ is the effective neutrino mass, where U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix diagonalizing the light neutrino mass matrix with eigenvalues m_i ($i = 1, 2, 3$). Using various updated NME calculations [13–19] and the recently reevaluated phase space factors [20] for the axial-vector coupling constant $g_A = 1.25$, we compare in Table I the upper limits on m_{ee}^{ν} for the canonical light neutrino contribution in Eq. (1) corresponding to the lower limits on ^{76}Ge and ^{136}Xe half-lives from GERDA [7] and KLZ [5], respectively. For comparison, we also give the corresponding ranges preferred by the updated KK claim [4] at 90% C.L. (assuming Gaussian errors). 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. It is evident that (i) the limits on m_{ee}^{ν} derived from ^{136}Xe are stronger than those from ^{76}Ge for all but one NME and (ii) the current GERDA-I limit either by itself or in combination with HM + IGEX does not *conclusively* rule out the updated KK claim at 90% C.L. independent of the NMEs, whereas the KLZ + EXO combined limit *does rule out* the KK claim for all but one NME. This shows the importance of complementary studies involving the correlation between ^{76}Ge and ^{136}Xe, as discussed below.

Their compatibility can be tested by comparing their half-lives using Eq. (1),

$$T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) = \frac{G_{0\nu}^{\mathrm{Ge}}}{G_{0\nu}^{\mathrm{Xe}}} \left| \frac{\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})}{\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})} \right|^2 T_{1/2}^{0\nu}(^{76}\mathrm{Ge}). \tag{2}$$

This can be used, for instance, to compare the KK claim [4] with the null results from KLZ [5] (see also [21]). Using the 90% C.L. range of $T_{1/2}^{0\nu}(^{76}\mathrm{Ge})$ preferred by the KK claim [4], we show in Table I the predicted range of $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ for the given NMEs [13–19]. An experimental limit on $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ larger than these predicted values will rule out the positive claim of [4] (for a given NME). From Table I we find that the KK claim is still compatible with the individual KLZ and EXO limits for some of the NMEs calculated by QRPA method [17–19], but inconsistent with their combined limit in [5] for all of the NME values, except the one given in [19], as also evident from the comparison of the effective mass. The reason is the very small NME for ^{136}Xe in [19], 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.

Equation (2) can also be used to study the future compatibility of ^{76}Ge and ^{136}Xe results, in case of a positive signal in one and a null result in another. For instance, if GERDA-II finds a signal at its projected sensitivity of $T_{1/2}^{0\nu}(^{76}\mathrm{Ge}) = 1.50 \times 10^{26}$ yr [22], then one can predict the corresponding $T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) = 2.92 \times 10^{25}$ yr for the EDF(U) NME [13] and 1.76×10^{26} yr for the SkM-HFB-QRPA [19] (with other NMEs in Table I giving intermediate values). Note that the prediction using EDF(U) NME will be already incompatible with the current KLZ + EXO combined limit [5], and the values for other NMEs will be incompatible with the future EXO-1T limit, $T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) > 8 \times 10^{26}$ yr [23].

For comparison of the experimental results with the canonical light neutrino contribution in 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 NMEs). Hence, we show in Fig. 1 the predicted half-lives for ^{76}Ge and ^{136}Xe as a function of the lightest

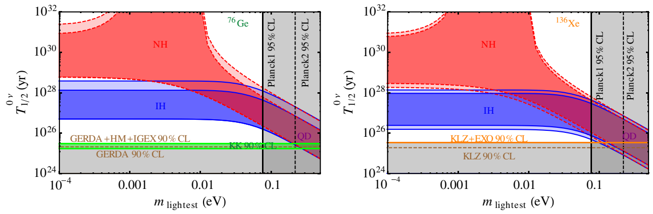

FIG. 1 (color online). $0\nu\beta\beta$ predictions in ^{76}Ge (left) and ^{136}Xe (right) due to light neutrino exchange. See text for details.

neutrino mass for normal and inverted mass orderings, including the hierarchical and quasidegenerate (QD) regimes. We have varied the oscillation parameters in their 3σ range [24], 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 [17] taken here for illustration), we recover the standard picture with the two (dark shaded) regions well separated. The green (solid) horizontal line in the left panel corresponds to the 90% C.L. KK claim value [4], whereas the brown (dashed and solid) horizontal lines correspond to the 90% C.L. lower limits set by GERDA and GERDA + HM + IGEX [7], respectively. The brown (dashed) and orange (solid) horizontal lines in the right panel represent the 90% C.L. lower limits for ^{136}Xe from KLZ and combined KLZ + EXO [5], respectively. The solid vertical line shows the 95% C.L. limit, $\sum m_\nu < 0.23$ eV (Planck1), derived from the Planck + WMAP low-multipole polarization + high resolution CMB + 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) [10].

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 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.

III. HEAVY NEUTRINO CONTRIBUTION

heavy right-handed (RH) neutrinos, introduced in the type-I seesaw [25] models, if sufficiently light ($\lesssim 10$ TeV) and can give a significant contribution to $0\nu\beta\beta$ [26] provided their mixing with the active neutrinos is sizable. However, this requires fine-tuning and/or cancellation [27]. A more natural way to obtain appreciable heavy neutrino contributions to the $0\nu\beta\beta$ amplitude arises in the TeV-scale LRSM [28] via RH currents [29,30]. 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 [31].

The LRSM naturally leads to small neutrino masses through either type-I seesaw via the RH neutrinos [25] or type-II seesaw via $SU(2)$ triplet scalars [32] or both [33]. There are several diagrams leading to $0\nu\beta\beta$ in LRSM (see [1] and references therein). Here we consider the appealing case of type-II dominance [29]. The scalar triplet contribution is expected to be small due to constraints from lepton flavor violation, which typically require the triplets to be heavy [29]. Hence, we focus only on the diagram with purely RH currents, mediated by the heavy neutrinos which adds to the purely LH light neutrino contribution given in Eq. (1). The corresponding half-life has a form similar to Eq. (1), with $|m^\nu_{ee}|^2$ replaced by $|m^{(\nu+N)}_{ee}|^2 = |m^\nu_{ee}|^2 + |m^N_{ee}|^2$, where m^N_{ee} is the heavy neutrino effective mass,

$$m^N_{ee} = \langle p^2 \rangle \frac{M^4_{W_L}}{M^4_{W_R}} \sum_j \frac{V^2_{ej}}{M_j}. \tag{3}$$

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. (3) is valid only in the heavy neutrino limit, $M^2_j \gg |\langle p^2 \rangle|$, which is assumed hereafter. Using the values for $\mathcal{M}_\nu$ and $\mathcal{M}_N$ from [17], we get $\langle p^2 \rangle = -(157\text{–}185\ \text{MeV})^2$ for ^{136}Xe and $-(153\text{–}184\ \text{MeV})^2$ for ^{76}Ge. The unitary matrix V in Eq. (3) diagonalizes M_R with mass eigenvalues M_j.

In the type-II limit, $M_\nu \approx m_L = (v_L/V_R) M_R$, where $m_L = f_L v_L$ and $m_R = f_R v_R$ in terms of the Yukawa couplings f_L and f_R, and the vacuum expectation values of the doublet and left (right)-triplet Higgs fields $v_{L(R)}$. We assume $f_L = f_R$ and $U = V$, i.e, the discrete LR symmetry is parity [34]. In Fig. 2, we show the half-life predictions for ^{76}Ge and ^{136}Xe, including the light and heavy neutrino NME ranges given in [17] (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 [35] 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. (3). The following important conclusions can be drawn from this illustrative plot: (i) The purely RH contribution, when added to the standard LH contribution,

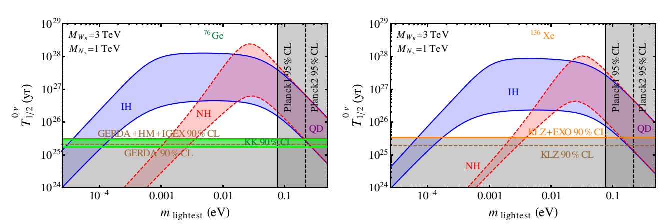

FIG. 2 (color online). The light + heavy neutrino contribution to $0\nu\beta\beta$ in ^{76}Ge (left) and ^{136}Xe (right) for both NH and IH, and with type-II seesaw dominance. Here $(M_{W_R}, M_{N_>}) = (3, 1)$ TeV. The vertical and horizontal lines are the same as in Fig. 1.

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 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. Needless to mention, the lower bound will become stronger with improved experimental bounds on $0\nu\beta\beta$ in the future; (iii) The KK claim can be reached for the lightest neutrino mass in the range of 1–4 for NH and 0.03–0.2 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. (2), with the NMEs for light neutrinos replaced by those for heavy neutrinos [17]. It predicts the half-life for ^{136}Xe in the range 0.56–2.74×10^{25} yr at 90% C.L. for all the corresponding NMEs in [17]. Thus in this case also, the KK claim is compatible with the individual KLZ and EXO bounds, but inconsistent with their combined limit. A 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 $m_{\rm lightest}$ 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. (3) is valid; otherwise, no lower limit on $m_{\rm lightest}$ 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. (3).

Using the experimental lower limits on $T^{0\nu}_{1/2}$, we also derive an upper limit on the quantity $M_{W_R}^{-4}\sum_j V_{ej}^2/M_j$ given in Eq. (3). Our results are given in Table II for the NMEs in [17]. Here "Argonne" and "CD-Bonn" stand for different nucleon-nucleon potentials, and "large" or "intm" refers

TABLE II. Upper limits on the heavy neutrino effective mass parameter corresponding to the 90% C.L. lower bounds on half-lives of ^{76}Ge (from GERDA and GERDA + HM + IGEX combined [7]) and ^{136}Xe (from KLZ and KLZ + EXO combined [5]) for the heavy neutrino NMEs in [17]. Also shown are its 90% C.L. preferred ranges of the KK claim [4].

	Limit on $M_{W_R}^{-4}\sum_j V_{ej}^2/M_j$ (TeV^{-5})				
	^{76}Ge			^{136}Xe	
SRQRPA NME method	GERDA	comb	KK	KLZ	comb
Argonne intm	0.30	0.25	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

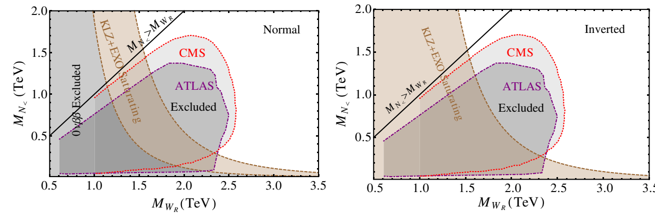

FIG. 3 (color online). The $0\nu\beta\beta$ constraints in the M_{W_R}-$M_{N_<}$ plane, along with the direct search limits from CMS and ATLAS. The brown (dashed) region saturates the KLZ + EXO combined limit, and the grey (white) region is excluded (allowed).

to the different size of the single-particle spaces in the model. From Table II we see that even with the heavy neutrino contribution, the incompatibility between the KK claim and the recent combined limits from ^{136}Xe experiments still persists. The limits from KLZ are found to be stronger than those from GERDA, similar to the light neutrino case.

IV. 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 total half-life saturates the combined limit from KLZ + EXO [5], 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 [24] 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 [17], which yield the smallest $|\langle p^2\rangle|$, and hence the strongest, limit in Fig. 3. The current LHC exclusion regions [35] are also shown for comparison (see also [36] for a detailed discussion on collider searches). We find that (i) for NH, a part of the parameter space not accessible at the LHC and can be constrained (or probed in case of an observation) through $0\nu\beta\beta$, and (ii) for IH, 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.

V. CONCLUSION

In summary, (i) we find the upper limit on the effective mass from KLZ to be more stringent than that from GERDA for all but one NME considered here; (ii) the recent limit on the half-life of ^{76}Ge from GERDA does not yet rule out the updated KK claim at 90% C.L., which is also compatible with the individual ^{136}Xe limits from EXO and KLZ due to NME uncertainties, whereas the combined ^{136}Xe limit excludes the KK claim for all but one NME calculation. This provides another test of the KK claim (for a given NME), complementary to the direct test by GERDA (independent of NMEs); (iii) the most stringent limit on $\sum m_\nu$ from Planck, in conjunction with the KLZ + EXO bound, excludes the possibility of saturating the limit for ^{136}Xe or the limit/claim in ^{76}Ge solely by the canonical light neutrino contribution; (iv) 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; and (v) for normal mass hierarchy, $0\nu\beta\beta$ puts additional constraints in the RH gauge boson and heavy neutrino mass plane, complementary to those from direct searches at the LHC.

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[1] For reviews, see e.g., W. Rodejohann, Int. J. Mod. Phys. E **20**, 1833 (2011); F. F. Deppisch, M. Hirsch and H. Pas, J. Phys. G **39**, 124007 (2012); J. D. Vergados, H. Ejiri and F. Simkovic, Rep. Prog. Phys. **75**, 106301 (2012); B. Schwingenheuer, Ann. Phys. (Amsterdam) **525**, 269 (2013).

[2] J. Schechter and J. W. F. Valle, Phys. Rev. D **25**, 2951 (1982).

[3] H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, A. Dietz and O. Chkvorets, Phys. Lett. B **586**, 198 (2004).

[4] H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, Mod. Phys. Lett. A **21**, 1547 (2006).

[5] A. Gando *et al.* (KamLAND-Zen Collaboration), Phys. Rev. Lett. **110**, 062502 (2013).

[6] M. Auger *et al.* (EXO Collaboration), Phys. Rev. Lett. **109**, 032505 (2012).

[7] M. Agostini *et al.* (GERDA Collaboration), Phys. Rev. Lett. **111**, 122503 (2013).

[8] H. V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A **12**, 147 (2001).

[9] C. E. Aalseth *et al.* (IGEX Collaboration), Phys. Rev. D **65**, 092007 (2002); **70**, 078302 (2004).

[10] P. A. R. Ade *et al.* (Planck Collaboration), arXiv:1303.5076.

[11] Note however that this depends strongly on the choice of cosmological data sets used.

[12] G. Fogli, E. Lisi, A. Marrone, A. Melchiorri, A. Palazzo, A. Rotunno, P. Serra, J. Silk, and A. Slosar, Phys. Rev. D **78**, 033010 (2008); M. Mitra, G. Senjanovic and F. Vissani, arXiv:1205.3867.

[13] T. R. Rodriguez and G. Martinez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).

[14] J. Menendez, A. Poves, E. Caurier and F. Nowacki, Nucl. Phys. **A818**, 139 (2009).

[15] J. Barea, J. Kotila and F. Iachello, Phys. Rev. C **87**, 014315 (2013).

[16] J. Suhonen and O. Civitarese, Nucl. Phys. **A847**, 207 (2010).

[17] A. Meroni, S. T. Petcov and F. Simkovic, J. High Energy Phys. 02 (2013) 025.

[18] F. Simkovic, V. Rodin, A. Faessler and P. Vogel, Phys. Rev. C **87**, 045501 (2013).

[19] M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).

[20] J. Kotila and F. Iachello, Phys. Rev. C **85**, 034316 (2012).

[21] J. Bergstrm, J. High Energy Phys. 02 (2013) 093; A. Faessler, G. L. Fogli, E. Lisi, V. Rodin, A. M. Rotunno, and F. Šimkovic, Phys. Rev. D **87**, 053002 (2013).

[22] A. A. Smolnikov (GERDA Collaboration), arXiv:0812.4194.

[23] M. Auger *et al.* (EXO Collaboration), JINST **7**, P05010 (2012).

[24] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, and A. M. Rotunno, Phys. Rev. D **86**, 013012 (2012).

[25] P. Minkowski, Phys. Lett. **67B**, 421 (1977); T. Yanagida, in *Workshop on United Theories*, KEK Report No. 79-18 1979, p. 95; M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity* (North Holland, Amsterdam, 1979), p. 315; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980).

[26] A. Ibarra, E. Molinaro and S. T. Petcov, J. High Energy Phys. 09 (2010) 108; M. Mitra, G. Senjanovic and F. Vissani, Nucl. Phys. **B856**, 26 (2012); J. Lopez-Pavon, S. Pascoli and C.-f. Wong, Phys. Rev. D **87**, 093007 (2013).

[27] A. Pilaftsis, Z. Phys. C **55**, 275 (1992); J. Kersten and A. Y. Smirnov, Phys. Rev. D **76**, 073005 (2007).

[28] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975).

[29] V. Tello, M. Nemevšek, F. Nesti, G. Senjanović, and F. Vissani, Phys. Rev. Lett. **106**, 151801 (2011).

[30] M. Nemevsek, F. Nesti, G. Senjanovic, and V. Tello, arXiv:1112.3061; J. Chakrabortty, H. Z. Devi, S. Goswami, and S. Patra, J. High Energy Phys. 08 (2012) 008; J. Barry and W. Rodejohann, J. High Energy Phys. 09 (2013) 153.

[31] W.-Y. Keung and G. Senjanovic, Phys. Rev. Lett. **50**, 1427 (1983).

[32] M. Magg and C. Wetterich, Phys. Lett. **94B**, 61 (1980); G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. **B181**, 287 (1981); R. N. Mohapatra and G. Senjanovic, Phys. Rev. D **23**, 165 (1981).

[33] J. Schechter and J. W. F. Valle, Phys. Rev. D **22**, 2227 (1980).

[34] Our conclusions remain unchanged for the other possibility, viz. charge conjugation under which $f_L = f_R^*$ and $U = V^*$.

[35] G. Aad *et al.* (ATLAS Collaboration), Eur. Phys. J. C **72**, 2056 (2012); The CMS Collaboration, CMS-PAS-EXO-12-017.

[36] S. P. Das, F. F. Deppisch, O. Kittel and J. W. F. Valle, Phys. Rev. D **86**, 055006 (2012).