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# Processes That Break Baryon Number by Two Units and the Majorana Nature of the Neutrino

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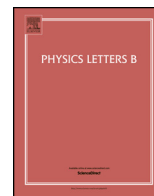
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# Processes that break baryon number by two units and the Majorana nature of the neutrino

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## ABSTRACT

We employ the simplest possible models of scalar-fermion interactions that are consistent with the gauge symmetries of the Standard Model and permit no proton decay to analyze the connections possible among processes that break baryon number by two units. In this context we show how the observation of  $n-\bar{n}$  oscillations and of a pattern of particular nucleon-antinucleon conversion processes – all accessible through e-d scattering – namely, selecting from  $e^-p \rightarrow e^+\bar{p}$ ,  $e^-p \rightarrow \bar{n}\bar{\nu}$ ,  $e^-n \rightarrow \bar{p}\bar{\nu}$ , and  $e^-n \rightarrow e^-\bar{n}$  would reveal that the decay  $\pi^-\pi^-\rightarrow e^-e^-$  must occur also. This latter process is the leading contribution to neutrinoless double beta decay in nuclei mediated by new short-distance physics, in contrast to that mediated by light Majorana neutrino exchange. The inferred existence of  $\pi^-\pi^-\rightarrow e^-e^-$  would also reveal the Majorana nature of the neutrino, though the absence of this inference would not preclude it.

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## 1. Introduction

The quantity baryon number (B) – lepton number (L), B–L, is exactly conserved in the Standard Model (SM), so that the observation of B–L violation would reveal the existence of new physics. In this letter we consider the possibility of the discovery of B–L violation within the realm of the strong interactions and the quark sector – and its broader implications. We focus particularly on processes that break baryon number by two units because proton decay, or, more generally, processes with  $|\Delta B| = 1$ , are not only unobserved but also have exceptionally strong empirical limits on their non-existence [1]. Moreover, as long known, the new-physics origins of  $|\Delta B| = 1$  and  $|\Delta B| = 2$  processes can be completely distinct [2–5].

The prospect of B–L violation is often discussed in the context of the fundamental nature of the neutrino; its violation would both make the  $|\Delta L| = 2$  process of neutrinoless double beta ( $0\nu\beta\beta$ ) decay possible and give the neutrino a Majorana mass [6–8], revealing that the neutrino can be regarded as its own antiparticle [9]. General parametrizations of the decay rate are associated with the long-range exchange of a light Majorana neutrino [10–12],

or through a short-range process mediated by new B–L violating dynamics at roughly the TeV scale [13]. The nuclear matrix elements, which are needed to interpret  $0\nu\beta\beta$  experiments, differ considerably in the two cases [10,13–16]. Systematic analyses of the possible operators of  $0\nu\beta\beta$  decay [17–20] and of the associated decay topologies [19], and of the decay rate within chiral effective theory [21–23] exist. The short-range mechanism is captured by  $\pi^-\pi^-\rightarrow e^-e^-$  [24] at leading order in hadron chiral effective theory [25], and the size of the associated hadronic matrix element has recently been computed in lattice QCD [26]. We believe that insight on the mechanisms of  $0\nu\beta\beta$  decay can be gleaned through the study of B–L violation in the quark sector, as it is the short-distance mechanism that can connect B–L violation with quarks to that with leptons.

The empirical study of  $|\Delta B| = 2$  processes has traditionally been associated with the search for  $n-\bar{n}$  oscillations with free or bound nucleons [2,27–29] and dinucleon decay in nuclei [4, 5,30–35]. Recently we have proposed the study of  $n-\bar{n}$  conversion [36,37], which, in contrast to  $n-\bar{n}$  oscillation, would not be spontaneous but mediated by an external source. In this letter we discuss the connections between these possibilities in the context of simple models of B and B–L violation. Motivated by “minimal” models for connectors to new hidden sectors [38,39], we introduce new scalar gauge bosons whose interactions are of mass dimension 3 and 4, so that the new interactions can be added to the SM in a theoretically consistent way. Scalar-fermion interactions in

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such models that respect the gauge symmetries of the SM have been studied in some detail [4,40,41]. In the current case our interest is in the models that permit  $|\Delta B| = 2$  transitions without proton decay, and indeed in those that do not permit  $|\Delta B| = 1$  transitions [4,5]. Interestingly, we have discovered that a variant of the models of Arnold, Fornal, and Wise [4] can be used to generate a  $|\Delta L| = 2$  transition, particularly, that of  $\pi^-\pi^- \rightarrow e^-e^-$ , whose existence drives the appearance of  $0\nu\beta\beta$  decay if mediated by new short-distance physics [25]. Thus in what follows we consider not only how particular  $n - \bar{n}$  oscillation and conversion processes can appear in these models, but we also show how such models can give rise to  $0\nu\beta\beta$  decay in nuclei – and we consider the interconnections between them. Particularly, we discuss how possible patterns of discovery of  $|\Delta B| = 2$  processes can reveal whether the short-distance dynamics that could give rise to  $\pi^-\pi^- \rightarrow e^-e^-$  can be shown to exist. In contrast, Babu and Mohapatra have shown that in the case of the  $SO(10)$  grand unified theory – and independently from the expected existence of the SM sphaleron – that if  $n - \bar{n}$  oscillations and a  $|\Delta B| = 1$  process were observed to occur that one could also conclude the existence of a Majorana neutrino [42]. Here we show that such a connection can be demonstrated without requiring the observation of proton decay, or indeed of any  $|\Delta B| = 1$  process. We emphasize that in this case, as in Ref. [42], the existence of such an inference does not imply that the short-distance mechanism ought saturate the experimental rate for  $0\nu\beta\beta$  decay. Our approach, however, is different from that of Ref. [42], as it relies on the use of minimal scalar models.

## 2. Minimal scalar models with baryon number violation but no proton decay

The minimal scalar models that give rise to  $|\Delta B| = 2$  and not  $|\Delta B| = 1$  processes while respecting SM gauge symmetries contain either three or four scalar interactions. Following Refs. [4,40,41,43] we consider all the interactions permitted by Lorentz and  $SU(3)_c \times SU(2)_L \times U(1)_Y$  gauge symmetry. Models for processes with both  $|\Delta B| = 1, 2$  have been constructed [4,41,43,44], though in this paper we follow Ref. [4]. The particular scalars that allow B or L violation to appear but do not admit  $|\Delta B| = 1$  processes at tree level are enumerated in Table 1. We have also noted the schematic interactions of the scalars  $X_i$  to right-handed leptons and quarks of generation  $a$  as  $e^a$  and  $u^a$ ,  $d^a$  and to left-handed leptons and quarks as  $L^a$  and  $Q^a$ , respectively. The symmetries of the scalar representations under color  $SU(3)$  and/or weak isospin  $SU(2)$  can fix the symmetry of the associated coupling constant under  $a, b$  interchange, and we have noted that as well in Table 1 – the relation  $g_i^{ab} = \pm g_i^{ba}$  indicates  $S(+)$  or  $A(-)$ , respectively, and “–” denotes no interchange symmetry. We note that  $X_9$  cannot generate a B and/or L violating interaction of mass dimension four or less, so that we do not consider it further, and that interactions denoted by “A” cannot involve only first-generation fermions.

In what follows we extend the models of Ref. [4] to include the possibility of  $|\Delta L| = 2$  processes as well. That earlier work focused on the possibility of  $|\Delta B| = 2$  processes without proton decay as mediated by interactions of the form  $X_a^2 X_b$  or  $X_a^3 X_b$ , where  $X_a$  and  $X_b$  are simply two distinct scalars that yield the SM gauge invariant interactions indicated, because it turns out not to be possible to add just one scalar and achieve that end. Here we enumerate all the possible B and/or L violating interactions that appear in mass dimension of four or less without regard to the number of different scalars that can appear. With three different scalars we can produce  $|\Delta L| = 2$  processes that also couple to quarks, and we study the connections between  $|\Delta B| = 2$  and  $|\Delta L| = 2$  processes explicitly.

**Table 1**

Scalar particle representations in the  $SU(3)_c \times SU(2)_L \times U(1)_Y$  SM that carry nonzero B and/or L but permit no proton decay at tree level, after Ref. [4]. We indicate the possible interactions between the scalar  $X$  and SM fermions schematically. Note that the indices  $a, b$  run over three generations, that the symmetry of the associated coupling  $g_i^{ab}$  under  $a \leftrightarrow b$  exchange is noted in brackets, and finally that our convention for  $Y$  is  $Q_{em} = T_3 + Y$ . Please refer to the text for further discussion.

Scalar	SM representation	B	L	Operator(s)	$[g_i^{ab}]$
$X_1$	(1, 1, 2)	0	–2	$X e^a e^b$	[S]
$X_2$	(1, 1, 1)	0	–2	$X L^a L^b$	[A]
$X_3$	(1, 3, 1)	0	–2	$X L^a L^b$	[S]
$X_4$	( $\bar{6}$ , 3, –1/3)	–2/3	0	$X Q^a Q^b$	[S]
$X_5$	( $\bar{6}$ , 1, –1/3)	–2/3	0	$X Q^a Q^b, X u^a d^b$	[A,–]
$X_6$	(3, 1, 2/3)	–2/3	0	$X d^a d^b$	[A]
$X_7$	( $\bar{6}$ , 1, 2/3)	–2/3	0	$X d^a d^b$	[S]
$X_8$	( $\bar{6}$ , 1, –4/3)	–2/3	0	$X u^a u^b$	[S]
$X_9$	(3, 2, 7/6)	1/3	–1	$X \bar{Q}^a e^b, X L^a \bar{u}^b$	[–,–]

We begin by fleshing out the precise interactions indicated in Table 1. Specifically, the possible scalar-fermion interactions mediated by each  $X_i$  are

$$\begin{aligned}
 & -g_1^{ab} X_1 (e^a e^b), \quad -g_2^{ab} X_2 (L^a \varepsilon L^b), \quad -g_3^{ab} X_3 (L^a \xi^A L^b), \\
 & -g_4^{ab} X_4^{\alpha\beta A} (Q_\alpha^a \xi^A Q_\beta^b), \quad -g_5^{ab} X_5^{\alpha\beta} (Q_\alpha^a \varepsilon Q_\beta^b), \quad -g_5^{ab} X_5^{\alpha\beta} (u_\alpha^a d_\beta^b), \\
 & -g_6^{ab} X_6^\alpha (d_\beta^a d_\gamma^b) \varepsilon^{\alpha\beta\gamma}, \quad -g_7^{ab} X_7^{\alpha\beta} (d_\alpha^a d_\beta^b), \quad -g_8^{ab} X_8^{\alpha\beta} (u_\alpha^a u_\beta^b),
 \end{aligned} \tag{1}$$

where  $\varepsilon = i\tau^2$  is a totally antisymmetric tensor,  $\xi^A \equiv ((1 + \tau^3)/2, \tau^1/\sqrt{2}, (1 - \tau^3)/2)$ , and  $\tau^A$  are Pauli matrices with  $A \in 1, 2, 3$ . We note  $\varepsilon\tau^A$  was used in place of  $\xi^A$  in Ref. [4], but that choice couples a single component of the scalar weak triplet to fermion states of differing total electric charge, incurring couplings that break electric charge conservation. The Greek indices are color labels, and we employ the  $SU(3)$  notation of Ref. [45] for fundamental and complex conjugate representations. We adopt 2-spinors such that the fermion products in parentheses are Lorentz invariant, and we map to 4-spinors via  $(u_{L,R\alpha} d_{L,R\beta}) \rightarrow (u_\alpha^T C P_{L,R} d_\beta)$  where  $C = i\gamma^0\gamma^2$  and  $P_{L,R} = (1 \mp \gamma_5)/2$  in Weyl representation [46].

## 3. Possible baryon-number and/or lepton-number violating processes

We now turn to the possible minimal scalar interactions that mediate either baryon and/or lepton number violation but conserve SM gauge symmetries. The possible interactions, including as many as four distinct scalars, are enumerated in Table 2. The models labeled M1–M9 are those of Models 1–9, respectively, in Ref. [4]. A particular model contains terms that couple the scalars to fermions and terms that couple the scalars to each other. We find we must modify the scalar self-couplings of M2 and M7 in order to maintain electric charge conservation for each term of the scalar self-interaction. Rather than recapitulate M1–M9 we simply summarize the detailed versions of the scalar forms enumerated in Table 2:

$$\begin{aligned}
 & \lambda_1 X_5^{\alpha\alpha'} X_5^{\beta\beta'} X_7^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\
 & \lambda_2 [X_4^{\alpha\alpha'} X_4^{\beta\beta'}]_0 X_7^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\
 & \lambda_3 X_7^{\alpha\alpha'} X_7^{\beta\beta'} X_8^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \quad \lambda_4 X_{6\alpha} X_{6\beta} X_8^{\alpha\beta}, \\
 & \lambda_5 X_5^{\alpha\alpha'} X_5^{\beta\beta'} X_5^{\gamma\gamma'} X_2 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\
 & \lambda_6 X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} X_2 \epsilon^{ABC} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\
 & \lambda_7 [X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} X_3^D]_0 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'},
 \end{aligned}$$

**Table 2**

Minimal interactions that break B and/or L from scalars  $X_i$  that do not permit  $|\Delta B| = 1$  interactions at tree level, indicated schematically, with the Hermitian conjugate implied. Interactions labeled M1–M9 appear in models 1–9 of Ref. [4]. Interactions A–G possess  $|\Delta L| = 2$ ,  $|\Delta B| = 0$ . M19, M20, and M21 follow from M8, M17, and M18 under  $X_7 \rightarrow X_6$ , respectively, but they do not involve first-generation fermions only.

Model		Model		Model	
M1	$X_5 X_5 X_7$	A	$X_1 X_8 X_7^\dagger$	M10	$X_7 X_8 X_8 X_1$
M2	$X_4 X_4 X_7$	B	$X_3 X_4 X_7^\dagger$	M11	$X_5 X_5 X_4 X_3$
M3	$X_7 X_7 X_8$	C	$X_3 X_8 X_4^\dagger$	M12	$X_5 X_5 X_8 X_1$
M4	$X_6 X_6 X_8$	D	$X_5 X_2 X_7^\dagger$	M13	$X_4 X_4 X_5 X_2$
M5	$X_5 X_5 X_5 X_2$	E	$X_8 X_2 X_5^\dagger$	M14	$X_4 X_4 X_5 X_3$
M6	$X_4 X_4 X_4 X_2$	F	$X_2 X_2 X_1^\dagger$	M15	$X_4 X_4 X_8 X_1$
M7	$X_4 X_4 X_4 X_3$	G	$X_3 X_3 X_1^\dagger$	M16	$X_4 X_7 X_8 X_3$
M8	$X_7 X_7 X_7 X_1^\dagger$			M17	$X_5 X_7 X_7 X_2^\dagger$
M9	$X_6 X_6 X_6 X_1^\dagger$			M18	$X_4 X_7 X_7 X_3^\dagger$

$$\begin{aligned} & \lambda_8 X_7^{\alpha\alpha'} X_7^{\beta\beta'} X_7^{\gamma\gamma'} X_1^\dagger \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_9 X_{6\alpha} X_{6\beta} X_{6\gamma} X_1^\dagger \epsilon^{\alpha\beta\gamma}, \end{aligned} \quad (2)$$

where Hermitian conjugation is implied. The noted weak singlets follow from SU(2) Clebsch–Gordon coefficients [1], so that

$$[X_4^{\alpha\alpha'} X_4^{\beta\beta'}]_0 \equiv \frac{1}{\sqrt{3}} [X_4^{\alpha\alpha'} X_4^{\beta\beta'} + X_4^{\alpha\alpha'} X_4^{\beta\beta'} - X_4^{\alpha\alpha'} X_4^{\beta\beta'}] \quad (3)$$

and

$$\begin{aligned} & [X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} X_3^D]_0 \equiv \frac{1}{\sqrt{3}} \left\{ \left[ \sqrt{\frac{3}{5}} X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} \right. \right. \\ & - \left( \sqrt{\frac{3}{20}} - \frac{1}{2} \right) X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} - \left( \sqrt{\frac{3}{20}} + \frac{1}{2} \right) X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} \\ & + \left( \sqrt{\frac{1}{60}} - \frac{1}{2} + \sqrt{\frac{1}{3}} \right) X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} \\ & + \left( \sqrt{\frac{1}{60}} + \frac{1}{2} + \sqrt{\frac{1}{3}} \right) X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} \\ & + \left( \sqrt{\frac{1}{15}} - \sqrt{\frac{1}{3}} \right) X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} \left. \right] X_3^3 + [“1” \leftrightarrow “3”] X_3^1 \\ & - \left[ \left( \sqrt{\frac{3}{20}} + \frac{1}{2} \right) (X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} + X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'}) \right. \\ & + \left( \sqrt{\frac{3}{20}} - \frac{1}{2} \right) (X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} + X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'}) \\ & - \left( \sqrt{\frac{1}{15}} - \sqrt{\frac{1}{3}} \right) (X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} + X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'}) \\ & \left. - \left( \sqrt{\frac{4}{15}} + \sqrt{\frac{1}{3}} \right) X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_4^{\gamma\gamma'} \right] X_3^2 \left. \right\}, \end{aligned} \quad (4)$$

where “1”  $\leftrightarrow$  “3” denotes the expression found by exchanging 1 and 3 superscripts. Turning to the  $|\Delta L| = 2$  models in Table 2, we find

$$\begin{aligned} & \lambda_A X_8^{\alpha\alpha'} (X_7^{\alpha\alpha'})^\dagger X_1, \quad \lambda_B [X_3^A X_4^{\alpha\alpha'}]_0 (X_7^{\alpha\alpha'})^\dagger, \\ & \lambda_C [X_3^A (X_4^{\alpha\alpha'})^\dagger]_0 X_8^{\alpha\alpha'}, \quad \lambda_D X_5^{\alpha\alpha'} (X_7^{\alpha\alpha'})^\dagger X_2, \quad \lambda_E X_8^{\alpha\alpha'} (X_5^{\alpha\alpha'})^\dagger X_2, \\ & \lambda_F X_2 X_2 X_1^\dagger, \quad \lambda_G [X_3^A X_3^B]_0 X_1^\dagger, \end{aligned} \quad (5)$$

**Table 3**

Suite of  $|\Delta B| = 2$  and  $|\Delta L| = 2$  processes generated by the models of Table 2, focusing on states with first-generation matter. The (\*) superscript indicates that a weak isospin triplet of  $|\Delta L| = 2$  processes can appear, namely  $\pi^0 \pi^0 \rightarrow \nu \nu$  and  $\pi^- \pi^0 \rightarrow e^- \nu$ . Models M7, M11, M14, and M16 also support  $\nu n \rightarrow \bar{\nu} \bar{\nu}$ , revealing that cosmic ray neutrinos could potentially mediate a  $|\Delta B| = 2$  effect.

$n\bar{n}$	$\pi^- \pi^- \rightarrow e^- e^-$	$e^- p \rightarrow \bar{\nu}_{\mu,\tau} \bar{n}$	$e^- p \rightarrow \bar{\nu}_e \bar{n} / e^+ \bar{p}$	$e^- p \rightarrow e^+ \bar{p}$
M1	A	M5	M7	M10
M2	B(*)	M6	M11	M12
M3	C(*)	M13	M14	M15
			M16	

whereas for the remaining baryon-number-violating models, we have

$$\begin{aligned} & \lambda_{10} X_7^{\alpha\alpha'} X_8^{\beta\beta'} X_8^{\gamma\gamma'} X_1 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{11} X_5^{\alpha\alpha'} X_5^{\beta\beta'} [X_4^{\gamma\gamma'} X_3^B]_0 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{12} X_5^{\alpha\alpha'} X_5^{\beta\beta'} X_8^{\gamma\gamma'} X_1 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{13} [X_4^{\alpha\alpha'} X_4^{\beta\beta'}]_0 X_5^{\gamma\gamma'} X_2 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{14} X_4^{\alpha\alpha'} X_4^{\beta\beta'} X_3^C X_5^{\gamma\gamma'} \epsilon^{ABC} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{15} [X_4^{\alpha\alpha'} X_4^{\beta\beta'}]_0 X_8^{\gamma\gamma'} X_1 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{16} [X_4^{\alpha\alpha'} X_3^B]_0 X_7^{\gamma\gamma'} X_8^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{17} X_5^{\alpha\alpha'} X_7^{\beta\beta'} X_7^{\gamma\gamma'} X_2^\dagger \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \\ & \lambda_{18} [X_4^{\alpha\alpha'} (X_3^B)^\dagger]_0 X_7^{\beta\beta'} X_7^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}, \end{aligned} \quad (6)$$

and Hermitian conjugation is implied throughout. Models with  $X_2$  and  $X_6$  couple to leptons and quarks of different generations. Only models M1, M2, and M3 can produce  $n - \bar{n}$  oscillations, though these models do not generate all the low-energy effective operators expected if SM gauge symmetry holds [37,47,48]. In particular, we find that M1 yields the operator  $(\mathcal{O}_2)_{RRR}$ , M2 yields  $(\mathcal{O}_1)_{LLR}$  and  $(\mathcal{O}_2)_{LLR}$  [47], though an operator relation combines these to  $(\mathcal{O}_3)_{LLR}$  [48] and M3 yields  $(\mathcal{O}_1)_{RRR}$ . An operator of form  $(\mathcal{O}_3)_{LLR}$  can also appear [47,48], but it is not generated in the minimal scalar-fermion models we consider.

Only models A, B, and C can produce  $\pi^- \pi^- \rightarrow e^- e^-$  decay, though B and C can also yield a weak isospin triplet of  $|\Delta L| = 2$  processes. These models all correspond to the second case of decay topology “T-II-3” in Ref. [19], as that decomposition considers the scalars’ electric and color charge only. At energies below the  $X_i$  mass scale, model A generates the operator combination  $\mathcal{O}_{3+}^{++} - \mathcal{O}_{3-}^{++}$ , whereas models B and C generate linear combinations of  $\mathcal{O}_{2\pm}^{++}$  [25].

#### 4. Phenomenology

The models of Table 2 possess a rich array of possible  $|\Delta B| = 2$  and  $|\Delta L| = 2$  processes. They also reveal the possibility of scattering-mediated  $|\Delta B| = 2$  processes, which we term “conversion” modes [36,37], and we show some of the more experimentally accessible ones in Table 3. As they are mediated by mass dimension 12 operators, they do not break B–L [49]. Other models show additional features. Models D and E support  $\pi^- \pi^0 \rightarrow e^- \nu_{\mu,\tau}$  and  $\pi^- \pi^0 \rightarrow \mu^- \nu_e$ , whereas F supports  $\mu^- \rightarrow e^- e^+ e^- \bar{\nu}_e \bar{\nu}_\mu$  and G supports  $e^+ e^- \rightarrow e^+ e^- \bar{\nu}_e \bar{\nu}_e$ . Models M8 and M18 can mediate  $mn \rightarrow \pi^+ \pi^+ e^- e^-$  decay, and finally M17 and M18 can yield  $e^+ n \rightarrow \bar{\Delta}^+ \nu_{\mu,\tau}$  and  $e^+ n \rightarrow \bar{\Delta}^+ \nu_e$  processes, respectively. We review the existing experimental constraints on the scalars we have considered in Sec. 6.





couplings) come from studies of  $t$ -quark final states [55–58], and flavor-physics constraints, while more severe, also involve second- and third-generation quark-scalar couplings [4,59–63]. Thus these constraints are not really pertinent to our case. However, there are also limits specific to scalars that couple to first-generation fermions; here we summarize findings that we plan to report on detail elsewhere [64]. Severe limits on  $pp \rightarrow e^+e^+$  in  $^{16}\text{O}$  have recently been reported by the Super-Kamiokande collaboration [65]. Such limits must be interpreted carefully because conventional physics can act to make the spontaneous process impossible, regardless of whether new physics is present. It has been claimed that earlier studies already limit the scalar mass scale to no less than 1.6 TeV [66], though that analysis neglects the role of Coulomb repulsion in the  $pp$  initial state. Its inclusion should weaken that bound by orders of magnitude. In addition,  $e^-p \rightarrow e^+\bar{p}$  from K-shell capture in  $^{16}\text{O}$  would not occur spontaneously because only the initial lepton can be in an atomic bound state. There are also astrophysical limits on hydrogen–antihydrogen ( $H - \bar{H}$ ) oscillation from attributing a measured excess of gamma radiation to the annihilation of  $\bar{H}$  atoms from  $H - \bar{H}$  oscillations [67]. That analysis neglects Galactic magnetic fields, which act to make the energy of  $H$  and  $\bar{H}$  unequal, quenching the oscillation probability. Magnetic fields of about 1 nT have been established in cold, HI clouds [68], and magnetic fields of no less than 0.1 nT exist in the warm interstellar medium [69]. Thus we believe that cold, HI regions continue to drive the assessed  $H - \bar{H}$  oscillation limit as estimated in Ref. [67]. Computing the  $H - \bar{H}$  energy splitting, we estimate the oscillation limit to be weakened by a factor of  $10^8$ . Collider searches for events with same-sign dileptons and multiple jets at the center-mass energies of  $\sqrt{s}=7, 8$ , and 13 TeV have been performed by the CMS collaboration [70–72]. Due to backgrounds from  $b$ -hadron decays, they reject same-sign dilepton events with an invariant mass of less than 8 GeV [70]. Thus, these collider constraints do not exclude possibility of models with scalars that couple to dileptons with masses that are less than 8 GeV. With these various refinements in place we believe that scalars with masses of  $\mathcal{O}(1\text{--}10\text{ GeV})$  are a viable possibility.

Models that support  $e^-p \rightarrow e^+\bar{p}$  have low-energy operators whose quark parts correspond to those found in  $n - \bar{n}$  oscillations under  $u \leftrightarrow d$  exchange. Exploiting this and a MIT bag model [73, 74] computation of  $\langle \bar{n} | \mathcal{O}_{1,2} | n \rangle$  [47,75] yields

$$\sigma \sim 1.5 \times 10^{-4} |g_4^{11}|^6 |\lambda_7|^2 |g_3^{11}|^2 \left( \frac{5 \text{ GeV}}{M_{X_4}} \right)^{12} \left( \frac{1 \text{ GeV}}{M_{X_3}} \right)^4 \text{ ab} \quad (7)$$

in model M7 for an electron beam energy of 155 MeV with a fixed target [76]. Model M7 contains scalars distinct from those that generate  $n - \bar{n}$  oscillations, and existing phenomenological analyses allow scalars in the  $\mathcal{O}(1\text{--}10\text{ GeV})$  mass range to appear. The experimental searches we propose, given Eq. (7) and the established accelerator and target capacities we have collected in Ref. [37], can discover or constrain them.

## 7. Summary

We have considered different physical processes that could reveal  $|\Delta B| = 2$  violation, both  $n - \bar{n}$  oscillation and conversion, and we have considered their interrelationships within minimal scalar-fermion models that support  $|\Delta B| = 2$  processes without proton decay. To realize this we have extended the models of Ref. [4] to include all possible minimal-scalar models that satisfy SM gauge invariance. Three distinct scalars are required to realize neutrinoless double  $\beta$  decay in these models, and Ref. [4] considered no more than two distinct scalars. Moreover, we have shown how the patterns of observation of particular  $|\Delta B| = 2$  processes would

speak to the existence of particular new scalars within these models, and we have employed Gell-Mann’s totalitarian principle [50] to invoke the new combination of these scalars needed to predict the existence of  $\pi^- \pi^- \rightarrow e^- e^-$  and thus of neutrinoless double  $\beta$  decay, though the latter connection also follows from a Feynman diagram approach once the particular  $|\Delta B| = 2$  processes are observed. Thus, finally, we conclude that the observation of particular  $|\Delta B| = 2$  processes could be used to infer the existence of a  $|\Delta L| = 2$  process,  $0\nu\beta\beta$  decay in nuclei, speaking to the Majorana nature of the neutrino and to new dynamics at accessible energy scales.

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## References

- [1] Particle Data Group Collaboration, C. Patrignani, et al., Review of particle physics, Chin. Phys. C 40 (2016) 100001.
- [2] R.N. Mohapatra, R.E. Marshak, Local B–L symmetry of electroweak interactions, Majorana neutrinos and neutron oscillations, Phys. Rev. Lett. 44 (1980) 1316–1319, Erratum: Phys. Rev. Lett. 44 (1980) 1643.
- [3] K.S. Babu, R.N. Mohapatra, Observable neutron anti-neutron oscillations in see-saw models of neutrino mass, Phys. Lett. B 518 (2001) 269–275.
- [4] J.M. Arnold, B. Fornal, M.B. Wise, Simplified models with baryon number violation but no proton decay, Phys. Rev. D 87 (2013) 075004.
- [5] P.S.B. Dev, R.N. Mohapatra, TeV scale model for baryon and lepton number violation and resonant baryogenesis, Phys. Rev. D 92 (2015) 016007.
- [6] S. Weinberg, Baryon and lepton nonconserving processes, Phys. Rev. Lett. 43 (1979) 1566–1570.
- [7] Y. Chikashige, R.N. Mohapatra, R.D. Peccei, Are there real Goldstone bosons associated with broken lepton number?, Phys. Lett. B 98 (1981) 265–268.
- [8] J. Schechter, J.W.F. Valle, Neutrino decay and spontaneous violation of lepton number, Phys. Rev. D 25 (1982) 774.
- [9] J. Schechter, J.W.F. Valle, Neutrinoless double beta decay in  $SU(2) \times U(1)$  theories, Phys. Rev. D 25 (1982) 2951.
- [10] H. Päs, M. Hirsch, H. Klapdor-Kleingrothaus, S. Kovalenko, Towards a superformula for neutrinoless double beta decay, Phys. Lett. B 453 (1999) 194–198.
- [11] F.F. Deppisch, M. Hirsch, H. Päs, Neutrinoless double beta decay and physics beyond the standard model, J. Phys. G 39 (2012) 124007.
- [12] J.C. Helo, M. Hirsch, T. Ota, Long-range contributions to double beta decay revisited, J. High Energy Phys. 06 (2016) 006.
- [13] H. Päs, M. Hirsch, H. Klapdor-Kleingrothaus, S. Kovalenko, A superformula for neutrinoless double beta decay II: the short range part, Phys. Lett. B 498 (2001) 35–39.
- [14] W.C. Haxton, G.J. Stephenson, Double beta decay, Prog. Part. Nucl. Phys. 12 (1984) 409–479.
- [15] J.D. Vergados, H. Ejiri, F. Simkovic, Theory of neutrinoless double beta decay, Rep. Prog. Phys. 75 (2012) 106301.
- [16] A. de Gouvea, P. Vogel, Lepton flavor and number conservation, and physics beyond the standard model, Prog. Part. Nucl. Phys. 71 (2013) 75–92.
- [17] K.S. Babu, C.N. Leung, Classification of effective neutrino mass operators, Nucl. Phys. B 619 (2001) 667–689.
- [18] A. de Gouvea, J. Jenkins, A survey of lepton number violation via effective operators, Phys. Rev. D 77 (2008) 013008.
- [19] F. Bonnet, M. Hirsch, T. Ota, W. Winter, Systematic decomposition of the neutrinoless double beta decay operator, J. High Energy Phys. 03 (2013) 055, Erratum: J. High Energy Phys. 04 (2014) 090.
- [20] M.L. Graesser, An electroweak basis for neutrinoless double  $\beta$  decay, J. High Energy Phys. 08 (2017) 099.
- [21] V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti, Neutrinoless double beta decay and chiral  $SU(3)$ , Phys. Lett. B 769 (2017) 460–464.
- [22] V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti, Neutrinoless double beta decay in chiral effective field theory: lepton number violation at dimension seven, J. High Energy Phys. 12 (2017) 082.
- [23] V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti, A neutrinoless double beta decay master formula from effective field theory, arXiv:1806.02780.
- [24] J.D. Vergados, Pion double charge exchange contribution to neutrinoless double beta decay, Phys. Rev. D 25 (1982) 914, Phys. Rev. D (1981) 771.
- [25] G. Prezeau, M. Ramsey-Musolf, P. Vogel, Neutrinoless double beta decay and effective field theory, Phys. Rev. D 68 (2003) 034016.
- [26] A. Nicholson, et al., Heavy physics contributions to neutrinoless double beta decay from QCD, arXiv:1805.02634.

- [27] V. Kuzmin, CP-noninvariance and baryon asymmetry of the Universe, JETP Lett. 12 (1970) 228, [http://www.jetpletters.ac.ru/ps/1730/article\\_26297.shtml](http://www.jetpletters.ac.ru/ps/1730/article_26297.shtml).
- [28] S.L. Glashow, Overview, in: Proceedings of Neutrino '79, vol. 1, 1979, p. 518.
- [29] R.N. Mohapatra, R.E. Marshak, Phenomenology of neutron oscillations, Phys. Lett. B 94 (1980) 183, Erratum: Phys. Lett. B 96 (1980) 444.
- [30] P.K. Kabir, Limits on  $n$  anti- $n$  oscillations, Phys. Rev. Lett. 51 (1983) 231.
- [31] J. Basecq, L. Wolfenstein,  $\Delta B = 2$  transitions, Nucl. Phys. B 224 (1983) 21.
- [32] Frejus Collaboration, C. Berger, et al., Lifetime limits on (B–L) violating nucleon decay and dinucleon decay modes from the Frejus experiment, Phys. Lett. B 269 (1991) 227–233.
- [33] R. Bernabei, et al., Search for the nucleon and di-nucleon decay into invisible channels, Phys. Lett. B 493 (2000) 12–18.
- [34] M. Litos, et al., Search for dinucleon decay into kaons in Super-Kamiokande, Phys. Rev. Lett. 112 (2014) 131803.
- [35] Super-Kamiokande Collaboration, J. Gustafson, et al., Search for dinucleon decay into pions at Super-Kamiokande, Phys. Rev. D 91 (2015) 072009.
- [36] S. Gardner, X. Yan, CPT, CP, and C transformations of fermions, and their consequences, in theories with B–L violation, Phys. Rev. D 93 (2016) 096008.
- [37] S. Gardner, X. Yan, Phenomenology of neutron–antineutron conversion, Phys. Rev. D 97 (2018) 056008.
- [38] J.D. Bjorken, R. Essig, P. Schuster, N. Toro, New fixed-target experiments to search for dark gauge forces, Phys. Rev. D 80 (2009) 075018.
- [39] B. Batell, M. Pospelov, A. Ritz, Exploring portals to a hidden sector through fixed targets, Phys. Rev. D 80 (2009) 095024.
- [40] A.J. Davies, X.-G. He, Tree level scalar fermion interactions consistent with the symmetries of the standard model, Phys. Rev. D 43 (1991) 225–235.
- [41] J.M. Arnold, B. Fornal, M.B. Wise, Phenomenology of scalar leptoquarks, Phys. Rev. D 88 (2013) 035009.
- [42] K.S. Babu, R.N. Mohapatra, Determining Majorana nature of neutrino from nucleon decays and  $n - \bar{n}$  oscillations, Phys. Rev. D 91 (2015) 013008.
- [43] J.P. Bowes, R. Foot, R.R. Volkas, Electric charge quantization from gauge invariance of a Lagrangian: a catalog of baryon number violating scalar interactions, Phys. Rev. D 54 (1996) 6936–6943.
- [44] S.M. Barr, X. Calmet, Observable proton decay from Planck scale physics, Phys. Rev. D 86 (2012) 116010.
- [45] T.P. Cheng, L.F. Li, Gauge Theory of Elementary Particle Physics, Clarendon (Oxford Science Publications), Oxford, UK, 1984.
- [46] H.K. Dreiner, H.E. Haber, S.P. Martin, Two-component spinor techniques and Feynman rules for quantum field theory and supersymmetry, Phys. Rep. 494 (2010) 1–196.
- [47] S. Rao, R. Shrock,  $n \leftrightarrow \bar{n}$  transition operators and their matrix elements in the MIT bag model, Phys. Lett. B 116 (1982) 238–242.
- [48] W.E. Caswell, J. Milutinovic, G. Senjanovic, Matter–antimatter transition on operators: a manual for modeling, Phys. Lett. B 122 (1983) 373–377.
- [49] A. Kobach, Baryon number, lepton number, and operator dimension in the standard model, Phys. Lett. B 758 (2016) 455–457.
- [50] M. Gell-Mann, The interpretation of the new particles as displaced charge multiplets, Nuovo Cimento 4 (1956) 848–866.
- [51] M. Baldo-Ceolin, et al., A new experimental limit on neutron–anti-neutron oscillations, Z. Phys. C 63 (1994) 409–416.
- [52] Super-Kamiokande Collaboration, K. Abe, et al., The search for  $n - \bar{n}$  oscillation in Super-Kamiokande I, Phys. Rev. D 91 (2015) 072006.
- [53] D. Milstead, A new high sensitivity search for neutron–antineutron oscillations at the ESS, PoS EPS-HEP 2015 (2015) 603, arXiv:1510.01569.
- [54] J. Alexander, et al., Dark Sectors 2016 workshop: community report, <http://inspirehep.net/record/1484628/files/arXiv:1608.08632.pdf>, 2016.
- [55] R.N. Mohapatra, N. Okada, H.-B. Yu, Diquark Higgs at LHC, Phys. Rev. D 77 (2008) 011701.
- [56] G. Cacciapaglia, H. Cai, A. Deandrea, T. Flacke, S.J. Lee, A. Parolini, Composite scalars at the LHC: the Higgs, the sextet and the octet, J. High Energy Phys. 11 (2015) 201.
- [57] ATLAS Collaboration, G. Aad, et al., Analysis of events with  $b$ -jets and a pair of leptons of the same charge in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector, J. High Energy Phys. 10 (2015) 150.
- [58] ATLAS Collaboration, G. Aad, et al., Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector, J. High Energy Phys. 08 (2015) 105.
- [59] K.S. Babu, R.N. Mohapatra, S. Nasri, Post-sphaleron baryogenesis, Phys. Rev. Lett. 97 (2006) 131301.
- [60] K.S. Babu, R.N. Mohapatra, S. Nasri, Unified TeV scale picture of baryogenesis and dark matter, Phys. Rev. Lett. 98 (2007) 161301, Phys. Rev. Lett. (2006) 651.
- [61] K.S. Babu, P.S. Bhupal Dev, R.N. Mohapatra, Neutrino mass hierarchy, neutron - anti-neutron oscillation from baryogenesis, Phys. Rev. D 79 (2009) 015017.
- [62] K.S. Babu, P.S. Bhupal Dev, E.C.F.S. Fortes, R.N. Mohapatra, Post-sphaleron baryogenesis and an upper limit on the neutron–antineutron oscillation time, Phys. Rev. D 87 (2013) 115019.
- [63] E.C.F.S. Fortes, K.S. Babu, R.N. Mohapatra, Flavor physics constraints on TeV scale color sextet scalars, in: Proceedings, 6th International Workshop on Charm Physics, Charm 2013, Manchester, UK, August 31–September 4, 2013, 2013, arXiv:1311.4101.
- [64] S. Gardner, X. Yan, 2019, in preparation.
- [65] Super-Kamiokande Collaboration, S. Sussman, et al., Dinucleon and nucleon decay to two-body final states with no hadrons in Super-Kamiokande, arXiv:1811.12430.
- [66] J. Bramante, J. Kumar, J. Learned, Proton annihilation at hadron colliders and Kamioka: high-energy versus high-luminosity, Phys. Rev. D 91 (2015) 035012.
- [67] Y. Grossman, W.H. Ng, S. Ray, Revisiting the bounds on hydrogen–antihydrogen oscillations from diffuse  $\gamma$ -ray surveys, Phys. Rev. D 98 (2018) 035020.
- [68] R.M. Crutcher, B. Wandelt, C. Heiles, E. Falgarone, T.H. Troland, Magnetic fields in interstellar clouds from Zeeman observations: inference of total field strengths by Bayesian analysis, Astrophys. J. 725 (2010) 466–479.
- [69] M. Haverkorn, Magnetic fields in the Milky Way, in: A. Lazarian, E.M. de Gouveia Dal Pino, C. Melioli (Eds.), Magnetic Fields in Diffuse Media, in: Astrophysics and Space Science Library, vol. 407, Jan. 2015, p. 483.
- [70] CMS Collaboration, S. Chatrchyan, et al., Search for new physics in events with same-sign dileptons and  $b$ -tagged jets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV, J. High Energy Phys. 08 (2012) 110.
- [71] CMS Collaboration, S. Chatrchyan, et al., Search for new physics in events with same-sign dileptons and jets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV, J. High Energy Phys. 01 (2014) 163, Erratum: J. High Energy Phys. 01 (2015) 014.
- [72] CMS Collaboration, V. Khachatryan, et al., Search for new physics in same-sign dilepton events in proton–proton collisions at  $\sqrt{s} = 13$  TeV, Eur. Phys. J. C 76 (2016) 439.
- [73] A. Chodos, R.L. Jaffe, K. Johnson, C.B. Thorn, V.F. Weisskopf, A new extended model of hadrons, Phys. Rev. D 9 (1974) 3471–3495.
- [74] A. Chodos, R.L. Jaffe, K. Johnson, C.B. Thorn, Baryon structure in the bag theory, Phys. Rev. D 10 (1974) 2599.
- [75] X. Yan, Neutron–Antineutron Transitions: Exploring B–L Violation with Quarks, PhD thesis, Kentucky U., 2017, [https://uknowledge.uky.edu/physastron\\_etds/46](https://uknowledge.uky.edu/physastron_etds/46).
- [76] D. Becker, et al., The P2 experiment – a future high-precision measurement of the electroweak mixing angle at low momentum transfer, arXiv:1802.04759.