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New Opportunities for the Study of Baryon Number Violation at Low-Energy Accelerators

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Abstract. I motivate new searches for baryon-number violation and consider, particularly, the prospects for detecting baryon number violation by two units at low-energy accelerators with intense electron beams, using ARIEL as a particular example.

1. Why Study Baryon-Number Violation?

The Standard Model (SM) of particle interactions offers no explanation for dark matter or dark energy, nor of nonzero neutrino masses and mixings; and with the measured Higgs mass, it is incompatible with a nonzero cosmic baryon asymmetry (BAU) [1, 2]. Thus each of these observed effects documents the existence of physics beyond the SM. The possibility of detectable baryon-number violation may be a key thread linking the solution to all of these puzzles. Certainly, baryon-number violation has long been considered an essential ingredient to the realization of a nonzero baryon asymmetry: B (baryon number), C (particle-antiparticle), and CP (matter-antimatter) violation must all exist in a non-equilibrium environment for a nonzero BAU to appear [3]. Yet in the SM, the electroweak phase transition is not of first order [1, 2], and baryon-number violation is only expected to occur at exceptionally high temperatures and thus be unobservable today. It is possible, however, that the cosmic origin of dark matter and ordinary baryonic matter are linked [4, 5, 6], with dark matter carrying a conserved charge analogous to baryon number. Perhaps baryon number is conserved across visible and dark sectors [7], suggesting the possibility of nucleon decays to dark final states [8]. Moreover, the existence of fundamental Majorana dynamics is signalled by the breaking of $B - L$ symmetry [9]. Thus through the breaking of L (lepton number) by two units the neutrino can gain an effective Majorana mass and thus generate neutrinoless double β decay, with the existence of the latter speaking to the former [10]. This physics can be studied in the baryon sector as well, with B broken by two units to give rise to $n\bar{n}$ oscillations.

2. Mechanisms of Baryon-Number Violation

Although the experimental limits on proton decay, or, more generally, $|\Delta B| = 1$ processes, are remarkably stringent [11], with partial lifetimes to particular final states in excess of 10^{32} years at 90% CL, processes in which baryon number changes by two (or more) units can be of distinct physical origin [12, 13, 14, 15, 16] and are also much less constrained [15, 16]. *Apparent* baryon-number violation is also possible: the neutron can decay to an invisible final-state that conserves baryon number. Since the final-state particles are undetected, the process makes it appear as if baryon number is broken. This last possibility has gained in interest because of the emergence, over the last decades, of an anomaly in measurements of the neutron lifetime: the lifetime determined from counting the protons that appear, e.g., the beam result $887.7 \pm 1.2\,(\mathrm{stat}) \pm 1.9\,(\mathrm{sys})\,\mathrm{s}$ [17], is significantly different from that determined counting the neutrons that persist, e.g., the bottle result $877.75 \pm 0.28\,(\mathrm{stat})^{+0.22}_{-0.16}\,(\mathrm{sys})\,\mathrm{s}$ [18]. Different explanations have been advanced for this difference; here we consider explanations that invoke hidden sectors with baryon number. The possibility that neutron-"mirror neutron" mixing could exist and be enhanced by the large magnetic fields used in the beam experiment [19], reducing the number of neutrons that decay, has been excluded as an explanation through a direct search [20]. The anomaly could be explained through dark decays of the neutron [21], via $n \to \chi\gamma$ or $n \to \chi e^+ e^-$, where the mass of χ must be chosen to evade $|\Delta B| = 1$ and nuclear stability constraints – see Fig. 1 for a concrete example. Constraints on this scenario exist also. Precision tests of the SM charged-weak current [22, 23, 24], as shown in Fig. 2, direct searches [25, 26, 27], and the existence of neutron stars of $2M_\odot$ in mass [28, 29, 30] all constrain the dark decay scenario, though modes such as $n \to 3\chi'$ [31] evade the last two constraints. Generally, the neutron dark decay rate can grossly exceed that of visible $|\Delta B| = 1$ decays by many orders of magnitude [24].

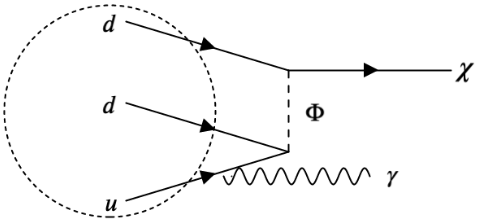

Figure 1. A microscopic, minimal model for $n \to \chi\gamma$ decay requires only a Dirac fermion χ, a SM singlet with $B = 1$, and a color-triplet, weak SU(2) singlet scalar Φ with hypercharge -1/3 and baryon number $-2/3$, as per [21].

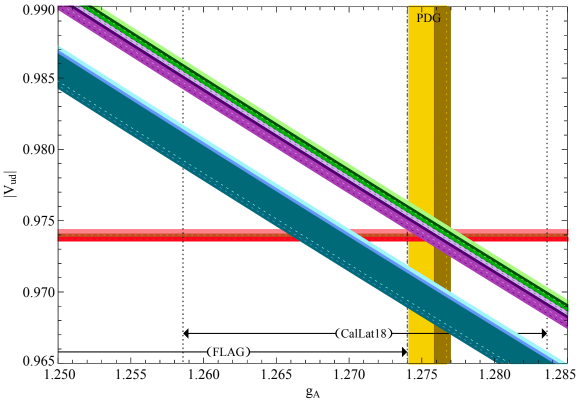

Figure 2. Constraints on the CKM element $|V_{ud}|$ and the axial coupling constant g_A in the SM, with different inputs and estimated radiative corrections (RCs), taken at 68% C.L. – see [24] for all details. Note the beam lifetime [17] (cyan), as well as the 2020 PDG average of bottle/trap lifetimes [32] (purple) and the latest magnetic trap result [33] (green) for different RCs. Values of g_A from lattice QCD are the 2021 FLAG average for $N_f = 2+1+1$ flavors [34] and the 2018 CalLat result [35]. The decay correlation determinations are from the PDG [32] and from [36] (ochre), with $|V_{ud}|$ from $0^+ \to 0^+$ nuclear β decays (red).

If we suppose that baryon number is broken at energies far above the weak scale, we can make a model-independent analysis of its low-energy breaking pattern through consideration of the new effective operators that appear [37]. Working in the context of the gauge symmetries and particle content of the SM [38, 39], the leading operators with mass dimension $d > 4$ are of the form

$$\mathcal{L}^{(d=6)}_{|\Delta B|=1} \supset \sum_i \frac{c_i}{\Lambda^2_{|\Delta B|=1}} (qqq\ell)_i + \text{h.c.} \tag{1}$$

and

$$\mathcal{L}^{(d=9)}_{|\Delta B|=2} \supset \sum_i \frac{c_i}{\Lambda^5_{|\Delta B|=2}} (qqqqqq)_i + \text{h.c.}\,, \tag{2}$$

for $|\Delta B| = 1$ and $|\Delta B| = 2$ transitions, respectively. Working in the Warsaw basis [39], with $c^{(\ell)}_{\chi\chi'} = 1$ and allowing one operator to act at a time, ultimately yields the constraints on $|\Delta B| = 1$ operators shown in Fig. 3. Thus we see that the scale of new physics in this case satisfies $\Lambda_{|\Delta B|=1} > 10^{14}$ GeV. In contrast, $|\Delta B| = 2$ transitions are engendered by higher mass dimension

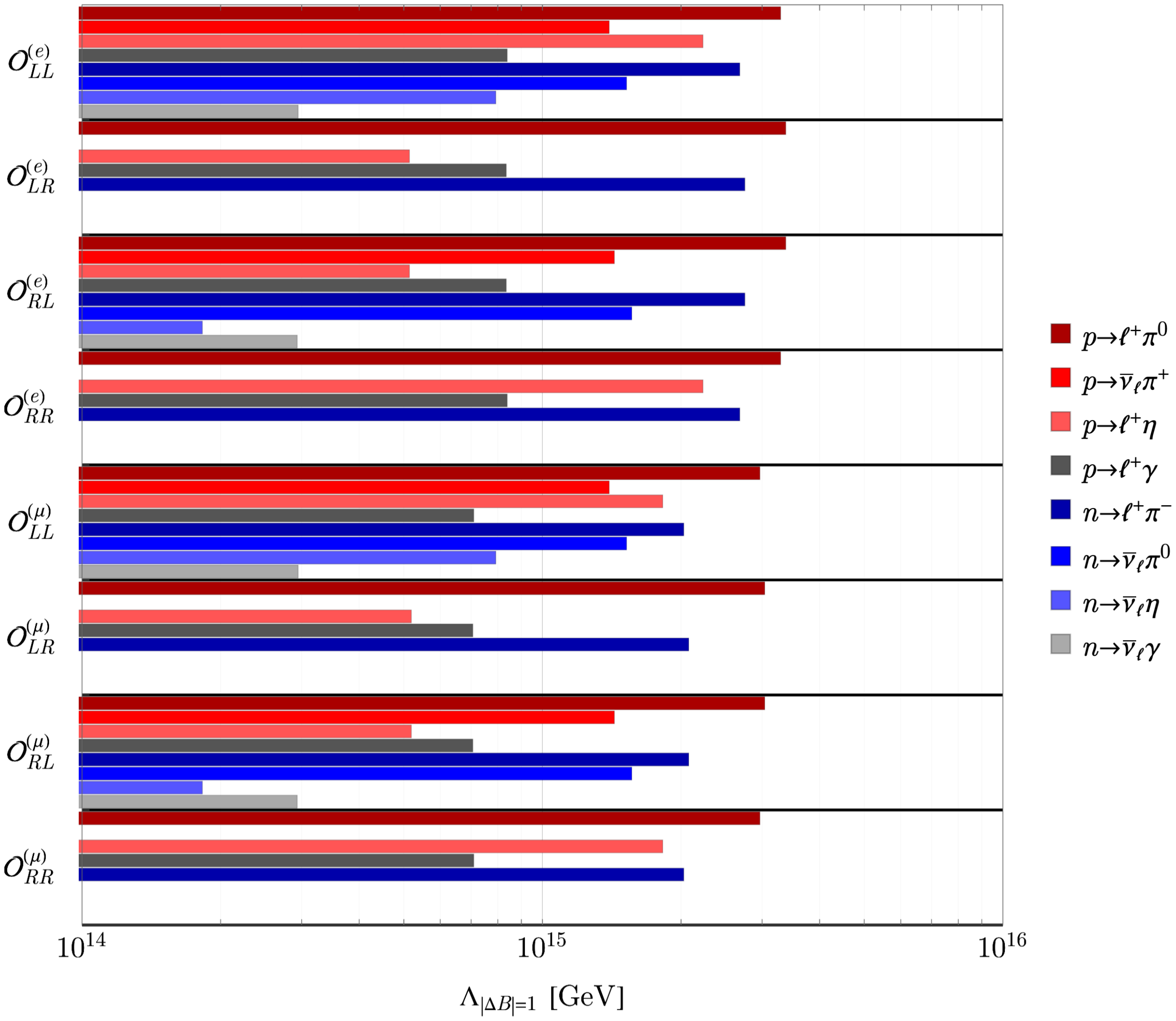

Figure 3. Constraints on individual $|\Delta B| = 1$ operators from experimental limits at 90% C.L., from [24]. The operators $\mathcal{O}^{(\ell)}_{\chi R}$ for $\chi \in L, R$ are not constrained by decays with antineutrino final states. Evading the different empirical constraints through the cancellation of different operator contributions is not tenable.

operators, so that we would expect a lower new-physics scale in this case. Using the experimental limit on $n\bar{n}$ oscillations [40, 41], a simple estimate yields $\Lambda_{|\Delta B|=2} \gtrsim 10^{5.5}\,\mathrm{GeV}$. Establishing the existence of $n - \bar{n}$ oscillations is of great importance, because it would demonstrate that fundamental Majorana dynamics exists in Nature, that the neutron also has a Majorana mass. Such a mass term is possible for any electrically neutral massive fermion, but the neutron's nonzero magnetic moment means that a Majorana neutron would be an entangled n and $\bar{n}$ state, whereas a Majorana neutrino can be a two-component field [42]. Nucleon-antinucleon transitions can be realized in different ways: through (i) searches for neutron-antineutron oscillations of free neutrons and in nuclei, (ii) searches for dinucleon decays in nuclei, and (iii) searches for nucleon-antinucleon conversion as mediated through a low-energy scattering process [43, 15]. The oscillation of a neutron into an antineutron would be a spontaneous process, and its likelihood is expected to be strongly suppressed by environmental effects that distinguish neutrons and antineutrons [44] – thus new experiments would be conducted under high vacuum with extreme magnetic field mitigation [45, 46]. Searches for dinucleon decays are limited by the finite density of the nucleus; if the BSM mediators are of much shorter range than the NN force, then dinucleon decays can be strongly suppressed by the likelihood of finding two nucleons sufficiently close together [15]. Here we focus on the last possibility, particularly that of $|\Delta B| = 2$ processes mediated by low-energy electron scattering [43, 15]. We find particular motivation for such studies in the connection they can provide between $n - \bar{n}$ oscillations and the short-range mechanism of neutrinoless double β decay, which we illustrate in Fig. 4. For context, we contrast different mechanisms of neutrinoless double β decay in Fig. 5; their relative size depends on the mechanism of new physics [48].

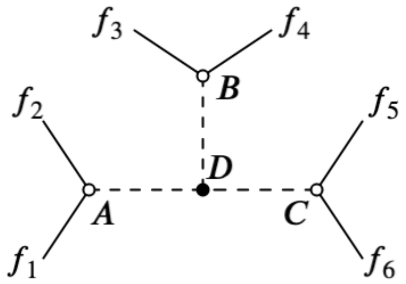

Figure 4. A short-range mechanism exploiting new $B-L$ violating dynamics to realize either $n-\bar{n}$ oscilations or neutrinoless double β decay, with the choices differentiated by the explicit fermion content $f_{1,...6}$ and new scalar or vector mediators that carry either B or L as appropriate to the context. It is possible to assert the existence of one given the observation of the other, if a $B - L$ conserving $|\Delta B| = 2$ process is also observed [15], and connecting the two via the observation of a $|\Delta B| = 1$ process is also possible [47, 24].

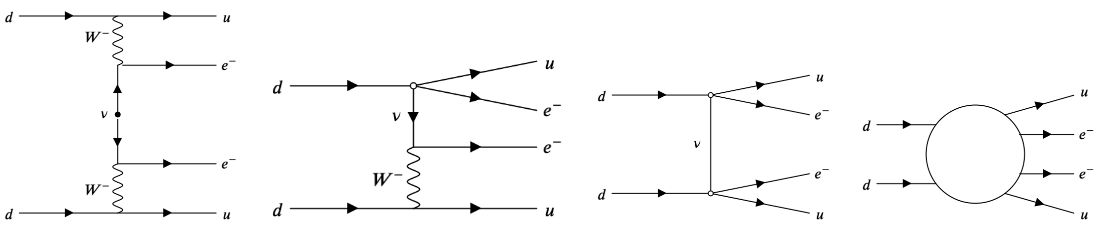

Figure 5. Mechanisms of neutrinoless double β decay, at the quark level, after [49]. The solid dot indicates a Majorana neutrino mass and hence the "mass mechanism," with open circles indicating effective interactions generated by new physics at a higher energy scale. The rightmost graph is the "short range" mechanism also shown in Fig. 4; within nuclei this can appear as $\pi^-\pi^- \to e^-e^-$ decay [48]. Analyses within effective field theory also exist [50, 51].

3. Modelling Baryon-Number Violation without Proton Decay

Given the severity of the constraints associated with $|\Delta B| = 1$ processes [24], we choose to model processes with $|\Delta B| = 2$ and/or $|\Delta L = 2|$ within minimal scalar models without proton decay [13, 14, 15]. That is, we consider all the models with renormalizable and SM gauge-invariant scalar-fermion interactions that do not mediate tree-level $|\Delta B| = 1$ processes, generalizing [13]. We enumerate the possible new scalars X_i in Table 1. The $(3, 1, -1/3)$ scalar in the model of Fig. 1 [21] does not appear because it mediates proton decay. With this set of X_i, B- and L- violating interactions appear through their mutual interactions, constructed to be of SM gauge invariant form: $X_i X_j X_k$ or $X_i X_j X_k X_l$. Since the interactions are all of mass dimension 4 or less, the associated masses and couplings are to be limited by experiment [15], very much in the spirit of "hidden sector" searches for dark photons and particles of similar ilk at intermediate-energy electron accelerators and elsewhere, note, e.g., Fig. 3.3 of [52]. The possible realizations of $|\Delta B| = 2$ and/or $|\Delta L| = 2$ violations that result are given in Table 2. Interactions with 4 X_i do not break $B - L$, but ones with 3 X_i do, as per SM expectations [53]. The interactions for a particular choice of X_i are

$$\mathcal{L}_{\rm int} \supset -g_1^{ab} X_1 (e^a e^b) - g_7^{ab} X_7^{\alpha\beta} (d^a_\alpha d^b_\beta) - g_8^{ab} X_8^{\alpha\beta} (u^a_\alpha u^b_\beta) - \lambda_3 X_7^{\alpha\alpha'} X_7^{\beta\beta'} X_8^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}$$
$$- \lambda_{10} X_7^{\alpha\alpha'} X_8^{\beta\beta'} X_8^{\gamma\gamma'} X_1 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'} - \lambda_A X_8^{\alpha\alpha'} (X_7^{\alpha\alpha'})^\dagger X_1 + \text{h.c.} \qquad (3)$$

Although each term has mass dimension 4 or less, at low energies $\mathcal{L}_{\rm int}$ generates a $d = 9$ operator to yield $n\bar{n}$ oscillations, a $d = 12$ operator to yield $e^- p \to e^+ \bar{p}$, and a $d = 9$ operator to yield $\pi^- \pi^- \to e^- e^-$ decay, i.e., a short-distance contribution to $0\nu\,\beta\beta$ decay. Feynman diagrams for these processes, working at energies for which X_1, X_7, X_8 can appear explicitly, are shown in Fig. 6. There are two different possible models, containing different X_i, that assert that $\pi^- \pi^- \to e^- e^-$ should exist if both $n\bar{n}$ oscillations and $e^- p \to e^+ \bar{p}$ are observed, and they are distinguished by whether $e^- p \to \bar{\nu}_X \bar{n}$, where the neutrino flavor is undetermined, or $e^- n \to e^- \bar{n}$ are also observed [15]. Thus high-intensity, low-energy electron scattering facilities, which may be under development to test new accelerator concepts [54], can also be used to broader purpose [43, 15]. In what follows we focus on the detectability of $e^- p \to e^+ \bar{p}$ and $e^- p \to \bar{\nu}_X \bar{n}$ in that context [55]. We note [16, 24] for broader discussions of the interconnections between processes that break $B - L$ by two or units.

Table 1. B- or L-carrying scalars that permit no proton decay at tree level, after [13, 15]. Possible scalar-fermion interactions are indicated schematically, with L-handed doublets L^a, Q^a and R-handed singlets e^a, u^a, d^a and generational indices a, b, noting the symmetry of the associated scalar-fermion couplings under $a \leftrightarrow b$ exchange. Note $Q_{\rm em} = T_3 + Y$.

Scalar	$SU(3)_c \times SU(2)_L \times U(1)_Y$	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	$X \bar{Q}^a e^b, X L^a \bar{u}^b$	[–,–]

Table 2. Minimal interactions of the scalars X_i of Table 1, indicated schematically, after [15]. Interactions labelled M1-M9 appear as models 1-9 in [13]. Interactions M1-M4 have $|\Delta B| = 2$, $|\Delta L| = 0$, whereas A-G have $|\Delta L| = 2$, $|\Delta B| = 0$. Further models follow from M8, M17, and M18 under $X_7 \to X_6$, but they cannot involve first-generation fermions only.

Model		Model		Model	
M1	$X_5X_5X_7$	A	$X_1X_8X_7^\dagger$	M10	$X_7X_8X_8X_1$
M2	$X_4X_4X_7$	B	$X_3X_4X_7^\dagger$	M11	$X_5X_5X_4X_3$
M3	$X_7X_7X_8$	C	$X_3X_8X_4^\dagger$	M12	$X_5X_5X_8X_1$
M4	$X_6X_6X_8$	D	$X_5X_2X_7^\dagger$	M13	$X_4X_4X_5X_2$
M5	$X_5X_5X_5X_2$	E	$X_8X_2X_5^\dagger$	M14	$X_4X_4X_5X_3$
M6	$X_4X_4X_4X_2$	F	$X_2X_2X_1^\dagger$	M15	$X_4X_4X_8X_1$
M7	$X_4X_4X_4X_3$	G	$X_3X_3X_1^\dagger$	M16	$X_4X_7X_8X_3$
M8	$X_7X_7X_7X_1^\dagger$			M17	$X_5X_7X_7X_2^\dagger$
M9	$X_6X_6X_6X_1^\dagger$			M18	$X_4X_7X_7X_3^\dagger$

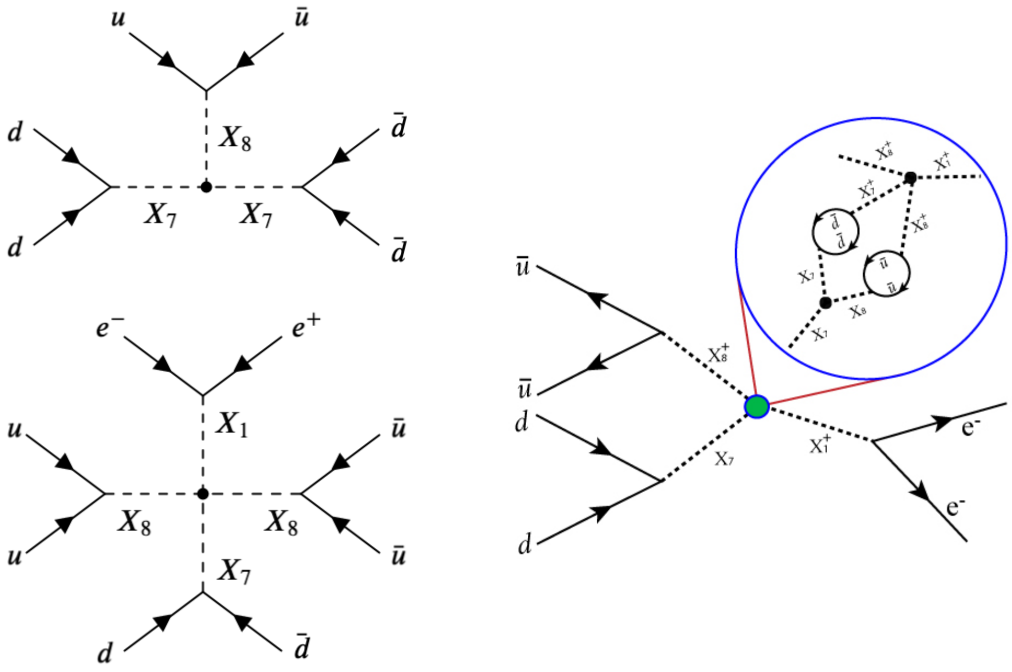

Figure 6. Connecting $n\bar{n}$ and $e^-p \to e^+\bar{p}$ to $\pi^-\pi^- \to e^-e^-$: if the first two processes are established, then the third must exist also [15], because anything not forbidden is compulsory [56].

4. Phenomenology of New Scalars: Existing Constraints

The new scalars we have noted find constraints from many sources [15, 55]. If the scalars couple to all three generations, then constraints from flavor physics, particularly from the $|\Delta F| = 2$ FCNCs and the neutron EDM limit, limit the different generational couplings significantly even if the scalar masses were well in excess of a TeV [13, 57, 58]. Here we suppose, rather, that the scalars couple to first-generation fermions only, so that these constraints do not apply. Although one might think that the new scalars, particularly the non-color-singlet ones, must nonetheless be of $\mathcal{O}(1\,\text{TeV})$ in mass [59], regions of parameter space associated with sub-$\mathcal{O}(10\,\text{GeV})$ masses are not yet excluded [15]. It is difficult to challenge this mass region at colliders due to QCD backgrounds [60], yet the new scalars all carry electric charge – and additional ingredients are required to negate would-be contributions to the width of the Z^0 gauge boson [61]. With these in place, we have constraints from the following sources, namely, from (i) the non-observation of $n-\bar{n}$ oscillations, though some model choices would not produce it, (ii) direct searches for same-sign dileptons at colliders, though to control backgrounds same-sign lepton pairs of the same flavor with an invariant mass of less than 8 GeV are rejected [62, 63], (iii) nuclear stability studies, particularly the limit on $pp \to e^+e^+$ and related modes from ^{16}O [64, 65], (iv) non-observation of GeV-scale gamma rays from hydrogen-antihydrogen ($\text{H}\bar{\text{H}}$) annihilation in hydrogen clouds [66, 67], and, finally, (v) indirect constraints from measurements of $(g-2)_e$ [68, 69, 61] and from parity-violating Møller scattering [70, 71, 61]. Both (iii) and (iv) stem from the non-observation of spontaneous processes which would conceivably occur if the needed new physics were present. However, conventional physics can act to make a spontaneous process impossible, in that it can (1) forbid a process through energy-momentum conservation or (ii) make the required initial configuration of particles impossible to realize, or it can negate the appearance of the supposed final state. The first possibility is long known in the hunt for free neutron-antineutron oscillations, requiring that searches be conducted in regions free from magnetic fields or from other matter [45, 46]. We note that Coulomb repulsion and binding-energy effects grossly reduce new-physics limits from ^{16}O stability studies, and galactic magnetic fields [72] weaken the ability of $\text{H}\bar{\text{H}}$ oscillations to occur [15]. The *Fermi* LAT collaboration has also noted a dearth of *expected* GeV-scale gamma rays, which they interpret as evidence for intergalactic magnetic fields [73]. The indirect limits of (v) constrain the scalar-electron couplings, with the most severe limit coming from the Moller E158 experiment [70], yielding $M_{X_{1,3}}/g^{11}_{1,3} \geq 2.7\,\text{TeV}$ at 90% CL for $M_{X_{1,3}} > 0.23\,\text{GeV}$ [61]. Employing this constraint we consider $0.23\,\text{GeV} < M_{X_{1,3}} < 8\,\text{GeV}$ and the colored scalars of Table 1 with masses between roughly $1-10\,\text{GeV}$ as viable possibilities.

5. Probing Baryon-Number Violation by 2 units at ARIEL

To compute $e^-p \to e^+\bar{p}$ or $e^-p \to \bar{\nu}\bar{n}$, e.g., we need to evaluate the Feynman diagram of $4X$ form shown in Fig. 6. In what follows I summarize the work of an upcoming paper with Xinshuai Yan [55]. At ARIEL energies, the new scalars cease to be dynamical degrees of freedom, and we can match that description to an effective theory in which a new 6-fermion contact interaction appears, noting that its prefactor has terms that scale as $(g_i^{11})^2/M^2_{X_i}$. Finally we can match that description to an effective hadron theory, in which the matching coefficient of the $e^T_\chi C e_\chi N^T_{\chi'} C p_{\chi'}$ effective operator is determined by the hadronic matrix element of the 4-quark operator computed in the M.I.T. bag model [74]. Since the momentum transfer in the process is small, i.e., $Q^2 \ll M^2_{X_i}$, we set $Q^2 = 0$ in our numerical assessment. Such bag-model estimates have been shown to compare fairly well with lattice QCD computations for $n\bar{n}$ oscillations [43]. Thus, finally, we can compute the cross sections – and event rates – we would expect for the various nucleon-antinucleon conversion processes of interest, mediated via the different scalar interaction models, as a function of the new scalar masses and couplings. Thus we can work beyond the naive dimensional analysis estimates previously employed [13, 15, 59].

Turning to the rate estimates, we choose $M_{X_i}/(|g_i^{11}|)^{1/2} = 30\,\text{GeV}$ for $i \in 1-3$ and $M_{X_i}/(|g_i^{11}|)^{1/2} = 1\,\text{GeV}$ for $i \in 4-8$ with $\lambda_j = 1$ for all j. We employ the e-linac beam mode at ARIEL [75] with a current of 10 mA and a beam energy of 40 MeV and a 100 cm long hydrogen target with density of $0.09 \times 10^{-3}\,\text{g/cm}^{-3}$ and assume an antinucleon detection efficiency of 100%. Thus we estimate that model M10, yielding $e^-p \to e^+\bar{p}$, would give about 13 events per year of running [55], with the various possible models giving outcomes roughly ranging from less than 1 event per year to about 150 events per year [55].

We emphasize that such rare processes can be identified in the environment of a low-energy, high-intensity electron scattering facility. The electron beam energy at ARIEL is far below pion-production threshold, so that the expected annihilation signature of a multi-pion final state should be striking. In a $n-\bar{n}$ experiment with cold neutrons such a signal is thought to be background free [45, 46]. We refer to [76] for an annihilation model for both free $\bar{p}p$ annihilation at rest and for $\bar{p}$ annihilation in complex targets, noting that the free proton model agrees favorably with experiment [77, 78] and the most likely outcome is a five-pion final state [79, 76]. Low-energy $\bar{n}p$ annihilation data exist as well, and although they appear to suggest a strong isoscalar component [80], a $\bar{p}p$-based analysis appears to give a reasonable indication of the expected annihilation outcomes [76]. For the low-energy processes we consider at ARIEL, we expect the annihilation process to be prompt and likely within the volume of the target.

6. Summary

We have considered the motivations for the study of baryon-number violation at low energies and have shown that new, possible avenues for B and/or L violation by 2 units, or more, have been largely overlooked. These studies can provide new insights into the nature of the neutrino. New scalars that could help mediate rare B and/or L-violating processes are associated with dimension $d \geq 9$ effective operators and are not excluded by existing experiments. Consequently we have considered the discovery potential of possible new experiments such as $e^-p \to e^+\bar{p}$ or $e^-p \to \bar{\nu}\bar{n}$. In a hydrogen target, the two possibilities should be distinguishable by the net electric charge of the produced multi-pion state. These possibilities could be fruitfully explored at an intense, low-energy electron accelerator such as ARIEL, and such prospects strengthen interest in $|\Delta B| = 2$ experiments of increased sensitivity.

Acknowledgments

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