



Baryon Number Violation in Neutrino Experiments

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September 7, 2022

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv:2203.08771 [hep-ex]

Searches for Baryon Number Violation in Neutrino Experiments: A White Paper

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ABSTRACT: Baryon number conservation is not guaranteed by any fundamental symmetry within the Standard Model, and therefore has been a subject of experimental and theoretical scrutiny for decades. So far, no evidence for baryon number violation has been observed. Large underground detectors have long been used for both neutrino detection and searches for baryon number violating processes. The next generation of large neutrino detectors will seek to improve upon the limits set by past and current experiments and will cover a range of lifetimes predicted by several Grand Unified Theories. In this White Paper, we summarize theoretical motivations and experimental aspects of searches for baryon number violation in neutrino experiments.

- Motivation for B-violation searches
- Poster child: Proton decay
 - Theory: Models, pheno, lattice
 - Experiments: Current and future
- Other BNV Processes
 - Neutron-antineutron oscillation
 - Di-nucleon decays
 - Exotic decay modes
- BSM Implications



[Figure from Symmetry Magazine]

- Electron is stable because of electric charge conservation.
- But proton stability is not guaranteed by any fundamental symmetry.
- In the SM, proton is stable due to an accidental global symmetry of baryon number (and $B - L$). [Weyl '29; Stückelberg '38; Wigner '49]

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- Also, B violation is an essential ingredient for baryogenesis. [Sakharov (JETP '67)]

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Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)

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Also S7, pp. 85–88]

The strong violation of the baryon charge during the superdense state and the fact that the baryons are stable in practice do not contradict each other. Let us consider a concrete model. We introduce interactions of two types.

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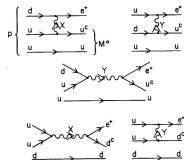
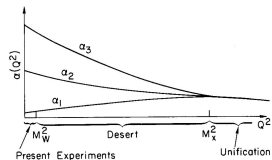
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Grand Unification and baryogenesis provide natural motivations for B searches.

Historical Context

- Quark-lepton unification in $SU(4)_c$. [Pati, Salam (PRL '73; PRD '74)]
- Grand Unification** of strong, weak and electromagnetic interactions at $Q \gtrsim M_X \gg M_Z$ in minimal $SU(5)$. [Georgi, Glashow (PRL '74)]
- Proton decay mediated by new gauge bosons which couple to both quarks and leptons, e.g. $p \rightarrow e^+ \pi^0$.
- Dim-6 operator ($QQQL$): Amplitude $\propto 1/M_X^2$.
- Lifetime: $\tau_p \sim \frac{16\pi^2 M_X^4}{g_{\text{GUT}}^4 m_p^5} \sim 10^{30}$ yr for $M_X \sim 10^{14}$ GeV. [Chanowitz, Ellis, Gaillard (NPB '77); Gavela, Le Yaouanc, Oliver, Pene, Raynal (PLB '81);...]
- Potential discovery with a sample of $\sim 10^{30}$ nucleons (a few tons of water) with an exposure of just a few years?



$$q_X = \frac{4}{3}$$

$$q_Y = \frac{1}{3}$$

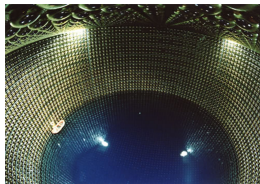
Kamiokande \rightarrow Super-K \rightarrow Hyper-K

- Original idea behind Kamiokande (Kamioka Nucleon Decay Experiment), started in 1983.
- 3 kt water $\sim 10^{32}$ nucleons.
- No proton decay observed and lower bound of $\tau_p \gtrsim 10^{32}$ yr placed.
- Ruled out minimal $SU(5)$ GUT.



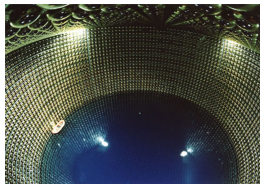
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- Upgraded to Super-Kamiokande (50 kt) in 1996.
- Currently sets the best limits on nucleon decay.
- Further upgrade to Hyper-K (990 kt) underway.
- Will push the proton lifetime limit to $\gtrsim 10^{35}$ yr.



Kamiokande \rightarrow Super-K \rightarrow Hyper-K

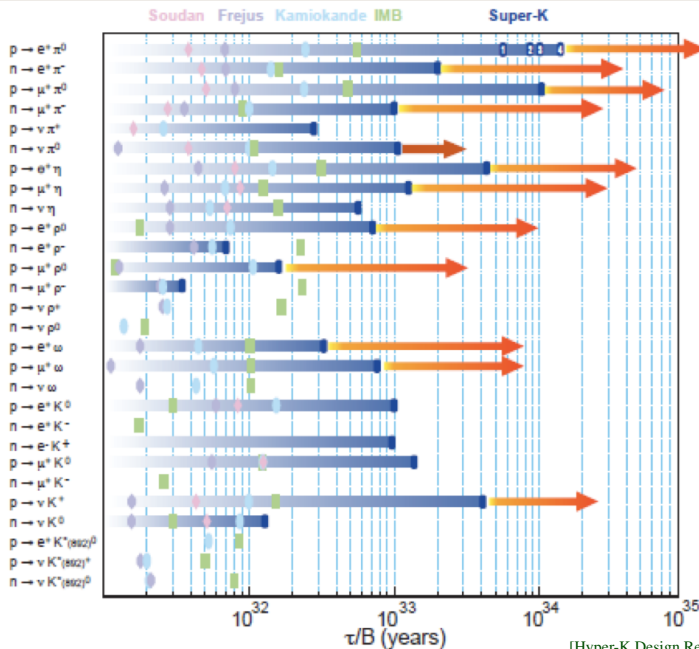
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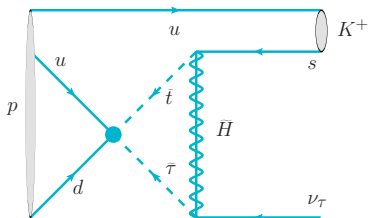
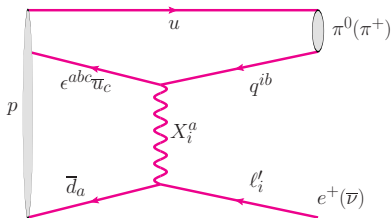
- Meanwhile, has been a very successful neutrino experiment.
- Detection of supernova neutrinos from SN1987A.
- Discovery of neutrino oscillations.
- K2K and T2K.

Next-generation large neutrino experiments have huge potential for \bar{B} searches.

Current Limits on Nucleon Decay



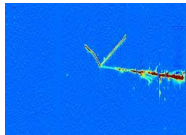
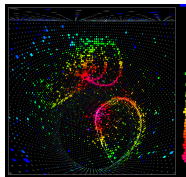
Dominant Proton Decay Modes



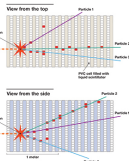
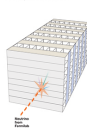
Modes (partial lifetime)	Current limit [90% CL] (10^{34} years)	Future Sensitivity [90% CL] (10^{34} years)
$\tau_p(p \rightarrow e^+ \pi^0)$	Super-K: 2.4 [55]	Hyper-K (1900 kton-yrs): 7.8 [56] DUNE (400 kton-yrs): ~ 1.0 [57] THEIA (800 kton-yrs): 4.1
$\tau_p(p \rightarrow \mu^+ \pi^0)$	Super-K: 1.6 [55]	Hyper-K (1900 kton-yrs): 7.7 [56]
$\tau_p(p \rightarrow \bar{\nu} K^+)$	Super-K: 0.66 [58]	Hyper-K (1900 kton-yrs): 3.2 [56] DUNE (400 kton-yrs): 1.3 [59] JUNO (200 kton-yrs): 1.9 [60] THEIA (800 kton-yrs): 3.8
$\tau_p(p \rightarrow \bar{\nu} \pi^+)$	Super-K: 0.039 [61]	—

Which Detector is the Best?

- Water Cherenkov (Super-K, Hyper-K) – Huge volume and large exposure time (hard to beat!)
- Liquid Argon TPC (MicroBooNE, DUNE) – excellent imaging capabilities
- Liquid scintillator (NOvA, JUNO) – Superb timing resolution
- Water-based liquid scintillator (THEIA) – large volume + good resolution



3D schematic of NOvA particle detector



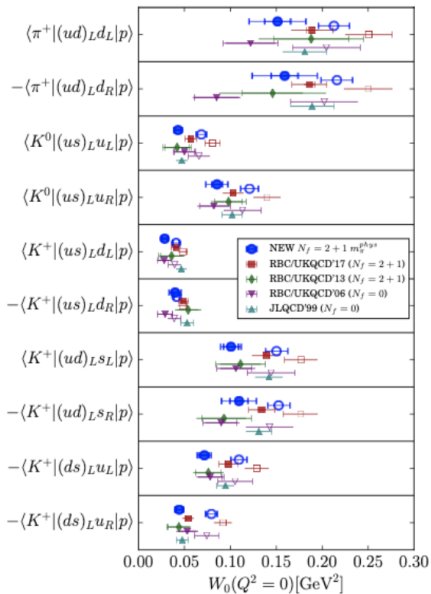
Theory Predictions (Non-SUSY Models)

Model	Decay modes	τ_N ($N = p, n$) [years]	Ref.
Non-SUSY minimal $SU(5)$	$p \rightarrow e^+ \pi^0$	$10^{30} - 10^{32}$	Georgi, Glashow [16]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \rightarrow e^+ \pi^0$	$\lesssim 2.3 \times 10^{36}$	Doršner, Saad [82]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \rightarrow e^+ \pi^0$ $p \rightarrow \bar{\nu} K^+$	$10^{32} - 10^{36}$ $10^{34} - 10^{37}$	Perez, Murgui [74]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-II seesaw)	$p \rightarrow \nu + (K^+, \pi^+, \rho^+)$ $n \rightarrow \nu + (\pi^0, \rho^0, \eta^0, \omega^0, K^0)$	$10^{31} - 10^{38}$	Doršner, Perez [64]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-III+I seesaw)	$p \rightarrow e^+ \pi^0$	$\lesssim 10^{36}$	Bajc, Senjanović [65]
Non-SUSY Extended $SU(5)$ (neutrino mass: 2-loop)	$p \rightarrow e^+ \pi^0$	$10^{34} - 10^{40}$	Saad [80]
Minimal flipped non-SUSY $SU(5)$	$p \rightarrow e/\mu^+ \pi^0$	$10^{38} - 10^{42}$	Arbeláez, Kolešová, Malinský [175]
Non-SUSY Minimal $SO(10)$	$p \rightarrow e^+ \pi^0$	$\lesssim 5 \times 10^{35}$	Babu, Khan [165]
Minimal $SO(10)$ with 45 Higgs	$p \rightarrow e^+ \pi^0$	$\lesssim 10^{36}$	Bertolini, Di Luzio, Malinský [176]
Minimal non-Renormalizable $SO(10)$	$p \rightarrow e^+ \pi^0$	$\sim 10^{35}$	Preda, Senjanović, Zantedeschi [173]
Non-SUSY Generic $SO(10)$	$p \rightarrow e^+ \pi^0$		Chakraborty, King, Maji [164]
$M_{\text{int}} : G_{422}$		$10^{34} - 10^{46}$	
$M_{\text{int}} : G_{422D}$		$10^{31} - 10^{34}$	
$M_{\text{int}} : G_{3221}$		$10^{36} - 10^{46}$	
$M_{\text{int}} : G_{3221D}$		$10^{33} - 10^{43}$	
Non-SUSY Generic E_6	$p \rightarrow e^+ \pi^0$		Chakraborty, King, Maji [164]
$M_{\text{int}} : G_{4221}$		$10^{27} - 10^{36}$	
$M_{\text{int}} : G_{4221D}$		$10^{27} - 10^{36}$	
$M_{\text{int}} : G_{333} \rightarrow G_{3221}$		$10^{32} - 10^{36}$	
$M_{\text{int}} : G_{4221D} \rightarrow G_{421}$		$10^{26} - 10^{48}$	
$M_{\text{int}} : G_{4221} \rightarrow G_{421}$		$10^{25} - 10^{48}$	

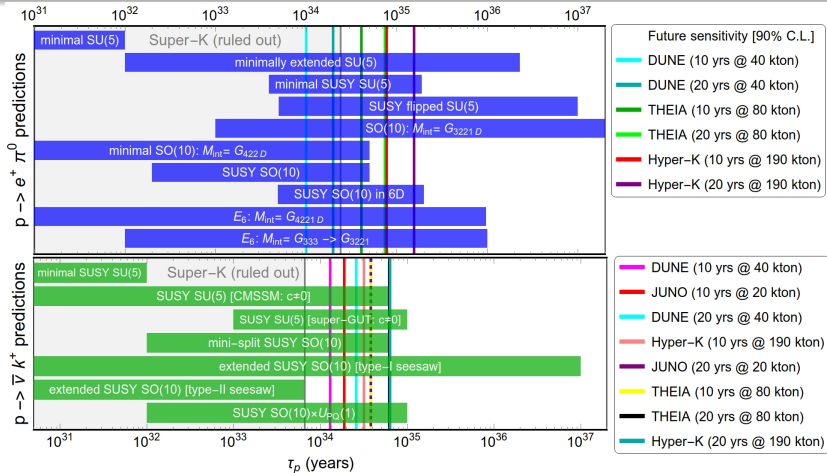
[BD, Koerner, Saad et al, 2203.08771]

Theory Predictions (SUSY Models)

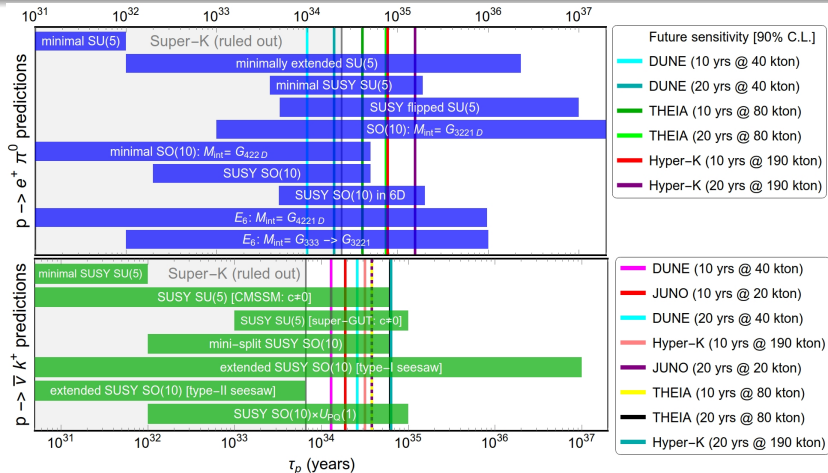
Model	Decay modes	τ_N ($N = p, n$) [years]	Ref.
Minimal SUSY $SU(5)$	$p \rightarrow \bar{\nu} K^+$ $n \rightarrow \bar{\nu} K^0$	$10^{28} - 10^{32}$	Dimopoulos, Georgi [42], Sakai [100] Hisano, Murayama, Yanagida [99]
Minimal SUSY $SU(5)$ (cMSSM)	$p \rightarrow \bar{\nu} K^+$ $p \rightarrow e^+ \pi^0$	$\lesssim (2-6) \times 10^{34}$ $10^{35} - 10^{40}$	Ellis et. al. [107]
Minimal SUSY $SU(5)$ ($\mathbf{5} + \mathbf{\bar{5}}$ matter fields)	$p \rightarrow \bar{\nu} K^+$ $p \rightarrow \mu^+ \pi^0 / K^0, n \rightarrow \bar{\nu} \pi^0 / K^0$	$\lesssim 4 \times 10^{33}$ $10^{33} - 10^{34}$	Babu, Bajc, Tavartkiladze [177]
SUGRA $SU(5)$	$p \rightarrow \bar{\nu} K^+$	$10^{32} - 10^{34}$	Nath, Arnowitt [103, 178]
mSUGRA $SU(5)$ (Higgs mass constraint)	$p \rightarrow \bar{\nu} K^+$	$3 \times 10^{34} - 2 \times 10^{35}$	Liu, Nath [111]
NUSUGRA $SU(5)$ (Higgs mass constraint)	$p \rightarrow \bar{\nu} K^+$	$3 \times 10^{34} - 10^{36}$	
SUSY $SU(5)$ or $SO(10)$ MSSM ($d = 6$)	$p \rightarrow e^+ \pi^0$	$\sim 10^{34.9 \pm 1}$	Pati [179]
Flipped SUSY $SU(5)$ (cMSSM)	$p \rightarrow e / \mu^+ \pi^0$	$10^{35} - 10^{37}$	Ellis et. al. [180–182]
Split SUSY $SU(5)$	$p \rightarrow e^+ \pi^0$	$10^{35} - 10^{37}$	Arkani-Hamed, et. al. [183]
SUSY $SU(5)$ in 5D	$p \rightarrow \mu^+ K^0$ $p \rightarrow e^+ \pi^0$	$10^{34} - 10^{35}$	Hebecker, March-Russell [184]
SUSY $SU(5)$ in 5D variant II	$p \rightarrow \bar{\nu} K^+$	$10^{36} - 10^{39}$	Alciati et.al. [185]
Mini-split SUSY $SO(10)$	$p \rightarrow \bar{\nu} K^+$	$\lesssim 6 \times 10^{34}$	Babu, Bajc, Saad [146]
SUSY $SO(10) \times U(1)_{PQ}$	$p \rightarrow \bar{\nu} K^+$	$10^{33} - 10^{35}$	Babu, Bajc, Saad [147]
Extended SUSY $SO(10)$ Type-I seesaw Type-II seesaw Inverse seesaw	$p \rightarrow \bar{\nu} K^+$	$10^{30} - 10^{37}$ $\lesssim 6.6 \times 10^{33}$ $\gtrsim 10^{34}$	Mohapatra, Severson [186] Mohapatra, Severson [186] Dev, Mohapatra [187]
SUSY $SO(10)$ with anomalous flavor $U(1)$	$p \rightarrow \bar{\nu} K^+$ $n \rightarrow \bar{\nu} K^0$ $p \rightarrow \mu^+ K^0$	$10^{32} - 10^{35}$	Shafi, Tavartkiladze [188]
SUSY $SO(10)$ MSSM	$p \rightarrow \bar{\nu} K^+$ $n \rightarrow \bar{\nu} K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$	Lucas, Raby [189], Pati [179]
SUSY $SO(10)$ ESSM	$p \rightarrow \bar{\nu} K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$	Pati [179]
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d = 5$)	$p \rightarrow \bar{\nu} K^+$ $p \rightarrow \mu^+ K^0$	$\gtrsim 2 \cdot 10^{34}$ $B \sim (1 - 50)\%$	Babu, Pati, Wilczek [190–192], Pati [179]
SUSY $SO(10) \times S_4$	$p \rightarrow \bar{\nu} K^+$	$\lesssim 7 \times 10^{33}$	Dev, Mohapatra, Dutta, Severson [193]
SUSY $SO(10)$ in 6D	$p \rightarrow e^+ \pi^0$	$10^{34} - 10^{35}$	Buchmuller, Covi, Wiesenfeldt [194]
GUT-like models from Type IIA string with D6-branes	$p \rightarrow e^+ \pi^0$	$\sim 10^{36}$	Klebanov, Witten [195]



Proton Decay Summary

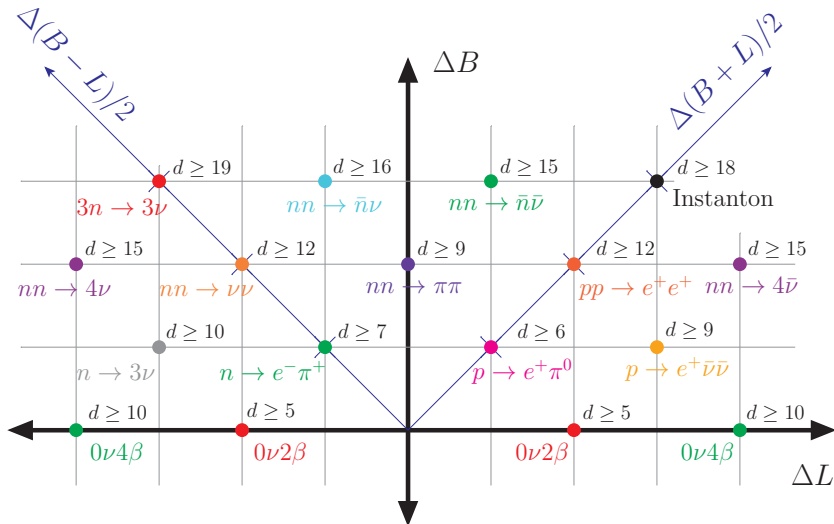


Proton Decay Summary



- *Disclaimer:* Just a representative set, not exhaustive.
- There is no single viable and predictive model for proton decay. [see talk by Senjanović]
- There are well-motivated models of B , where proton is absolutely stable. [see talk by Plascencia]

Other B Violating Modes



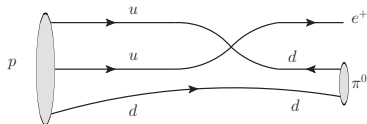
[Heeck, Takhistov, 1910.07647 (PRD '20)]

$\Delta B = 1$ versus $\Delta B = 2$

$$\Delta B = 1$$

- Proton decay
- Induced by dimension-6 operator $QQQL$.
- Amplitude $\propto \Lambda^{-2}$.
- $\tau_p \gtrsim 10^{34}$ yr implies $\Lambda \gtrsim 10^{15}$ GeV.
- Proton decay requires GUT-scale physics.

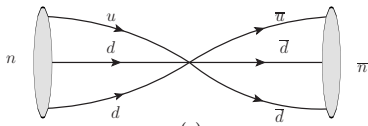
[Nath, Perez (Phys. Rep. '07)]



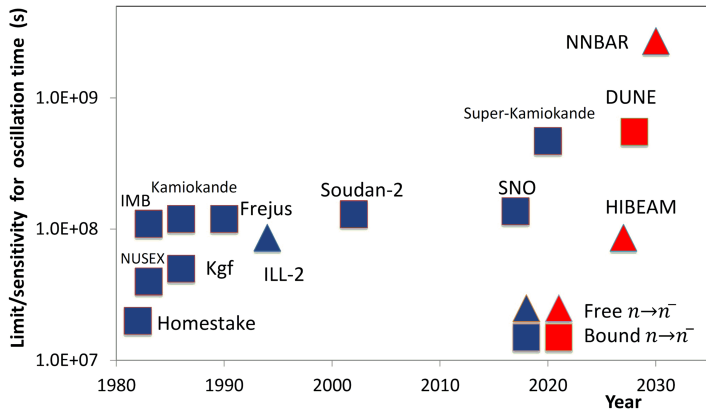
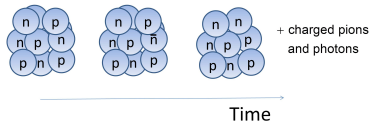
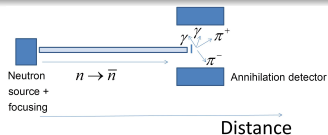
$$\Delta B = 2$$

- Di-nucleon decay and $n - \bar{n}$
- Induced by dimension-9 operator $qqqqqq$.
- Amplitude $\propto \Lambda^{-5}$.
- $\Lambda \gtrsim 100$ TeV enough to satisfy experimental constraints ($\tau_{n\bar{n}} \gtrsim 10$ yr).
- $n - \bar{n}$ oscillation (and conversion) could come from a TeV-scale new physics.

[Phillips et al. (Phys. Rep '16)]



$n - \bar{n}$: Experimental Status



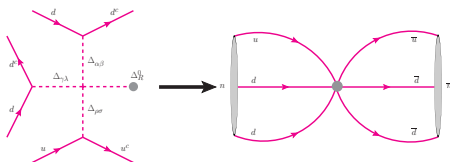
[Milstead, BD et al., 2006.04907 (J. Phys. G '21)]

Well-motivated Theory

- Connected to $B - L$ breaking and Majorana neutrino mass. [Mohapatra, Marshak (PRL '80)]
- UV-complete embedding in Pati-Salam partial unification with $SU(4)_c \times SU(2)_L \times SU(2)_R$. [Babu, BD, Mohapatra (PRD '08)]
- Under $SU(2)_L \times U(1)_Y \times SU(3)_c$,

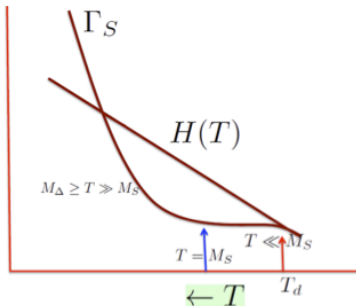
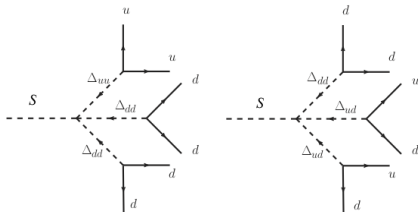
$$\begin{aligned} \Delta(1, 3, \overline{10}) = & \Delta_{uu}(1, -\frac{8}{3}, \mathbf{6}^*) \oplus \Delta_{ud}(1, -\frac{2}{3}, \mathbf{6}^*) \oplus \Delta_{dd}(1, +\frac{4}{3}, \mathbf{6}^*) \\ & \oplus \Delta_{ue}(1, \frac{2}{3}, \mathbf{3}^*) \oplus \Delta_{u\nu}(1, -\frac{4}{3}, \mathbf{3}^*) \\ & \oplus \Delta_{de}(1, \frac{8}{3}, \mathbf{3}^*) \oplus \Delta_{d\nu}(1, \frac{2}{3}, \mathbf{3}^*) \\ & \oplus \Delta_{ee}(1, 4, 1) \oplus \Delta_{\nu e}(1, 2, 1) \oplus \Delta_{\nu\nu}(1, 0, 1) . \end{aligned}$$

$$\Delta_{\nu\nu} = v_{BL} + \frac{1}{\sqrt{2}}(S + iG^0)$$



A Model of Post-Sphaleron Baryogenesis

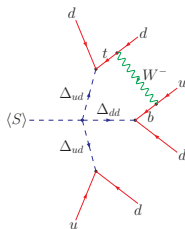
[Babu, Mohapatra, Nasri (PRL '06)]



Conditions for PSB:

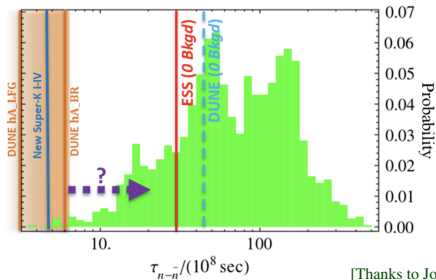
- $\Gamma_{S \rightarrow 6q} \leq H(T_{EW})$, and $\Lambda_{QCD} \leq T_d \leq T_{EW}$.
- $S \rightarrow 6q$ must be the dominant decay mode (over $S \rightarrow Z f \bar{f}, ZZ$) $\implies v_{BL} \gtrsim 100 \text{ TeV}$.
- Vacuum stability restricts v_{BL} from being arbitrarily large: $\lambda v_{BL} \lesssim 2\sqrt{\pi} M_\Delta$.
- Not too much dilution: $d \equiv \frac{s_{\text{before}}}{s_{\text{after}}} \simeq \frac{g_*^{-1/4} 0.6 \sqrt{\Gamma_S M_{Pl}}}{n_S M_S / s(T_d)} \sim \frac{T_d}{M_S} \implies M_S \lesssim 17 \text{ TeV}$.

Theoretical Upper Limit on $n - \bar{n}$ Oscillation Time



Leads to an *upper limit* on the $n - \bar{n}$ oscillation time.

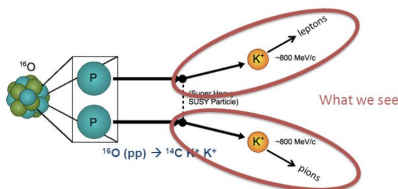
[Babu, BD, Fortes, Mohapatra (PRD '13); Babu, Chauhan, BD, Mohapatra (work in progress), taking into account new lattice result from Rinaldi, Syritsyn, Wagman, Buchoff, Schroeder, Wasem (PRL '19; PRD '19)]



[Thanks to Josh Barrow for the experimental lines] 19

Dinucleon Decays

- Induced by the same dim-9 operators that give rise to $n - \bar{n}$ oscillation.
- Stringent limits from Super-K.



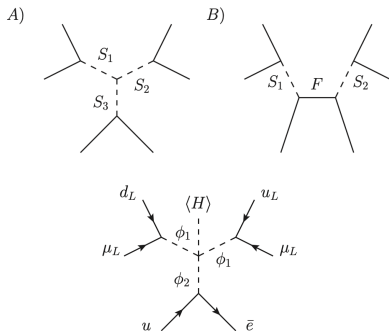
Decay Mode	$ \Delta(B - L) $	τ/B (90% C.L.)
$pp \rightarrow K^+ K^+$	2	1.7×10^{32} yrs. ^b
$pp \rightarrow \pi^+ \pi^+$	2	7.2×10^{31} yrs. ^b
$np \rightarrow e^+ \nu$	$0(\bar{\nu}), 2(\nu)$	2.6×10^{32} yrs. ^b
$np \rightarrow \mu^+ \nu$	$0(\bar{\nu}), 2(\nu)$	2.0×10^{32} yrs. ^b
$np \rightarrow \tau^+ \nu$	$0(\bar{\nu}), 2(\nu)$	3.0×10^{31} yrs. ^b
$np \rightarrow \pi^+ \pi^0$	2	1.7×10^{32} yrs. ^b
$nn \rightarrow \pi^0 \pi^0$	2	4.0×10^{32} yrs. ^b

[Takhistov, 1605.03235]

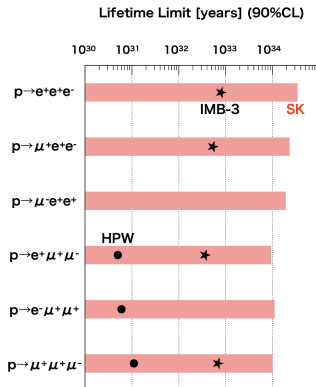
- In a given model with carefully chosen flavor structure, possible to satisfy the dinucleon bounds, while having observable $n - \bar{n}$, and vice versa. [see e.g. Dev, Mohapatra (PRD '15); Grojean, Shakya, Wells, Zhang (PRL '18); Fridell, Harz, Hati (JHEP '21)]

Trilepton Decay Modes

- In models with lepton flavor symmetries.
- Induced by $d \geq 9$ operators.
- Unavoidably induce lepton flavor non-universality.

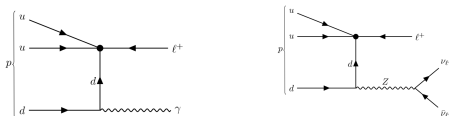


[Hambye, Heeck, 1712.04871 (PRL '18)]



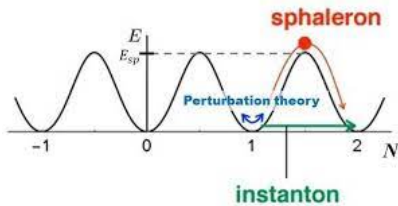
[Super-K, 2001.08011 (PRD '20)]

Other Exotic Decay Modes



decay mode	$(\tau/B)_{\text{exp. l.bnd.}}$	Ref.	$(\tau/B)_{p \rightarrow \ell + \gamma; \text{est. l.bnd.}}$
$p \rightarrow e^+ \gamma$	41	[14]	$\sim 10 - 10^2$
$p \rightarrow \mu^+ \gamma$	24	[14]	$\sim 10 - 10^2$
$p \rightarrow e^+ \gamma \gamma$	1.00	[20]	$\sim 10^4$
$p \rightarrow \mu^+ \gamma \gamma$	NA	NA	$\sim 10^4$
$n \rightarrow \bar{\nu} \gamma$	0.55	[15]	$\sim 1 - 10$
$n \rightarrow \bar{\nu} \gamma \gamma$	2.19	[13]	$\sim 10^3$
$p \rightarrow e^+ e^+ e^-$	0.793	[13]	$\sim 10^4$
$p \rightarrow \mu^+ e^+ e^-$	0.529	[13]	$\sim 10^4$
$p \rightarrow e^+ \mu^+ \mu^-$	0.359	[13]	$\sim 10^4$
$p \rightarrow \mu^+ \mu^+ \mu^-$	0.675	[13]	$\sim 10^4$
$n \rightarrow \bar{\nu} e^+ e^-$	0.257	[13]	$\sim 10^3$
$n \rightarrow \bar{\nu} \mu^+ \mu^-$	0.079	[13]	$\sim 10^3$
$n \rightarrow \bar{\nu} \mu^+ e^-$	0.083	[13]	$\sim 10^{11}$
$p \rightarrow \bar{\nu} e^+ \nu_e$	0.17	[18]	$\sim 10^{12}$
$p \rightarrow \bar{\nu} \mu^+ \nu_\mu$	0.22	[18]	$\sim 10^{12}$
$n \rightarrow \bar{\nu} \nu \bar{\nu}$	0.58×10^{-3}	[19]	$\sim 10^{11}$

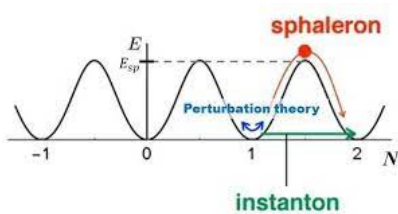
[Girmohanta, Shrock, 1910.08106 (PRD '19)]



$$E_{\text{Sph}} = \frac{2m_W}{\alpha_W} B\left(\frac{m_H}{m_W}\right)$$

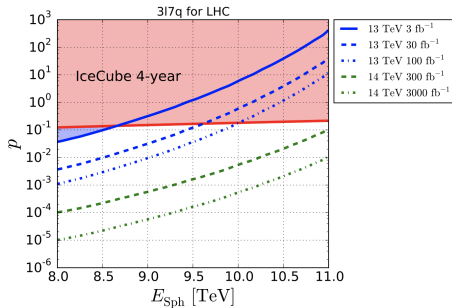
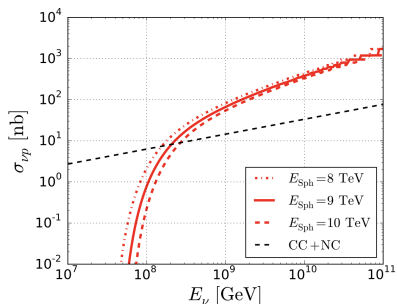
$$\simeq 9 \text{ TeV} \quad (\text{for } m_H = 125 \text{ GeV})$$

Sphalerons at IceCube



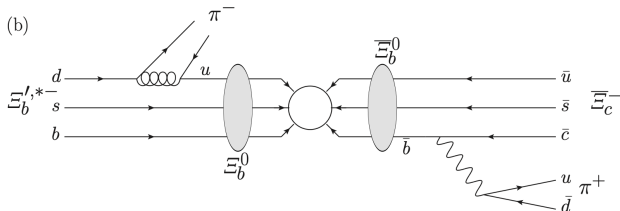
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[Ellis, Sakurai, Spannowsky, 1603.06573 (JHEP '16)]

- Baryon-antibaryon oscillations (e.g. $\Xi_b^0 - \bar{\Xi}_b^0$) at LHCb. [1708.05808 (PRL '17)]



- Direct searches at the LHC (e.g. within RPV SUSY context). [see talk by Osojnak]
- Flavor observables. [see talks by Kuno, Neumeister, de Bruyn, Davidson]
- Gravitational wave signatures. [see talk by Turner]

For a nice review on experimental signatures of GUT-scale physics, see [Croon, Gonzalo, Graf, Košnik, White, 1903.04977 (Front. Phys. '19)]

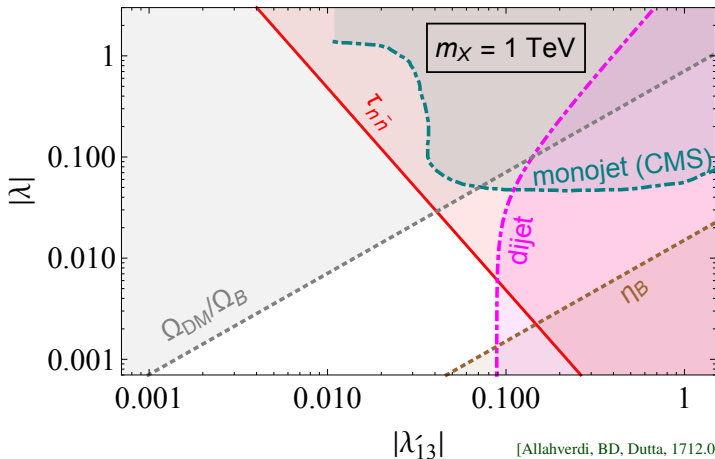
Connection to Dark Matter

- A simple effective model of \mathcal{B} : [Allahverdi, Dutta (PRD '13); BD, Mohapatra (PRD '15)]

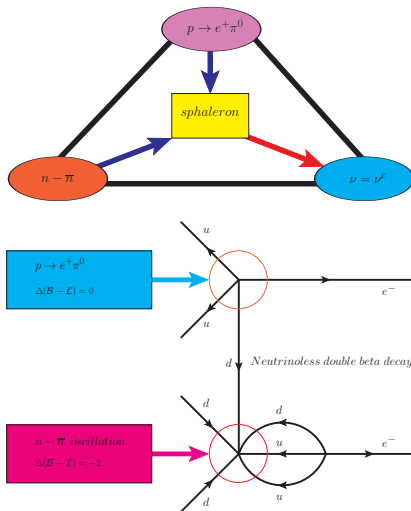
$$\mathcal{L} \supset \lambda_{\alpha i} X_{\alpha} \psi u_i^c + \lambda'_{\alpha i j} X_{\alpha}^* d_i^c d_j^c + \frac{1}{2} m_{\psi} \bar{\psi}^c \psi + \text{H.c.}$$

- ψ is a SM-singlet Majorana fermion and can be a DM candidate if

$$m_p - m_e \leq m_{\psi} \leq m_p + m_e.$$



Big Picture: BSM Implications of \mathcal{B}



[Babu, Mohapatra (PRD '15)]

Observation of \mathcal{B}/\mathcal{L} can falsify high-scale baryogenesis/leptogenesis. [see talk by Harz]

- Observation of BNV will be a clear signal of BSM physics.
- The best limits come from large-scale neutrino experiments like Super-K.
- Expected nucleon lifetimes in a wide class of GUT models are within reach of current and future large-scale underground neutrino experiments.
- Important to study as many BNV channels as possible.
- Neutron-antineutron oscillation should be treated with the same level of importance as proton decay.
- Many complementary laboratory probes of BNV.
- Connection to other BSM physics: neutrino mass, baryogenesis, dark matter, gravitational waves, flavor physics.

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Thank You!