Neutrinoless double beta decay without proton decay

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Based, in part, on…
Susan Gardner and X.Y., arXiv:1602.00693, 1808.05288, 1810.XXXX.

Origin of neutrino mass

- **Neutrino oscillation**
  - Neutrino flavor-changing oscillations
    Observed by Super-K and Sudbury Neutrino Observatory
  - (therefore) neutrinos have mass

Takaaki Kajita

Arthur B. McDonald

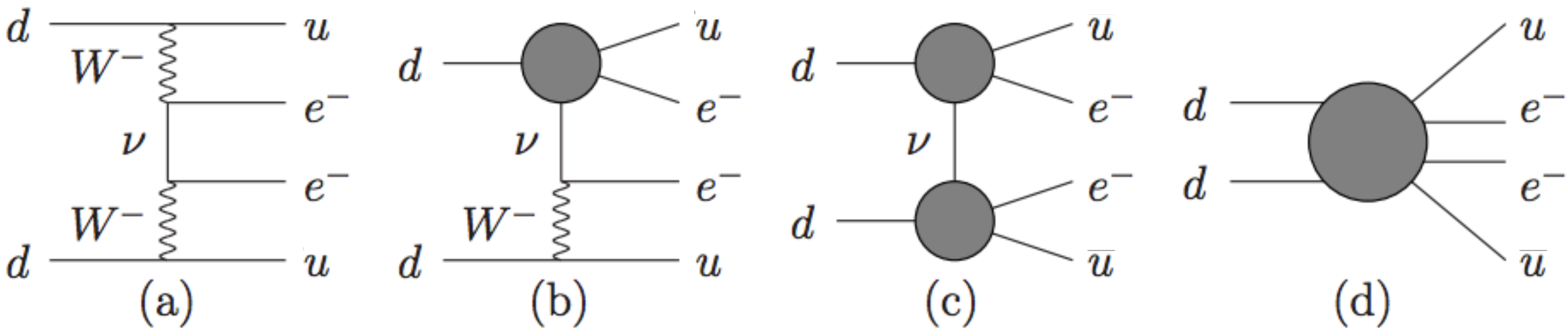
- **Majorana or Dirac neutrinos?**
  - If Dirac, like other fermions in SM, it can be generated by the Higgs mechanism (a right-handed v field is needed)
  - If Majorana, a dimension five mass term appears [Weinberg, (1979)]

❖ Observation of neutrinoless double ($0v\beta\beta$) decay shows that L is broken by two units and neutrino has an effective Majorana mass. [Schechter & Valle, (1982)]

Mechanisms of $0\nu\beta\beta$ decay

$0\nu\beta\beta$ is mediated by a mass dimension [d]= 9 operator:

$\mathcal{O} \propto \bar{u}\bar{u}dd\bar{e}\bar{e}$ $\quad$ *Or* $\pi^-\pi^- \rightarrow e^-e^-$



[Bonnet et al (2013)]

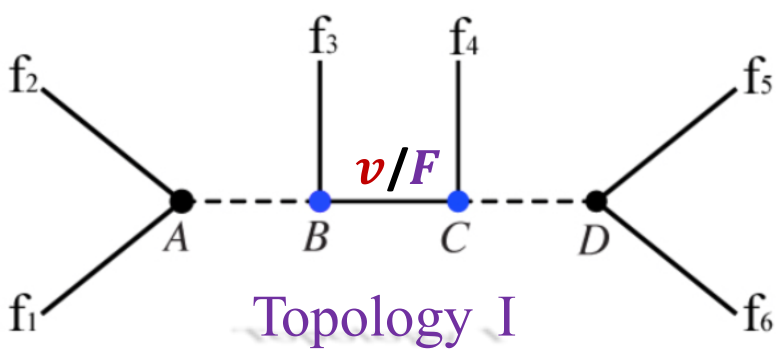
- (a)-(c): A light neutrino is exchanged --- "*long-range*" diagrams;
- (d): Mediated by heavy particles --- "*short-range*" diagram.

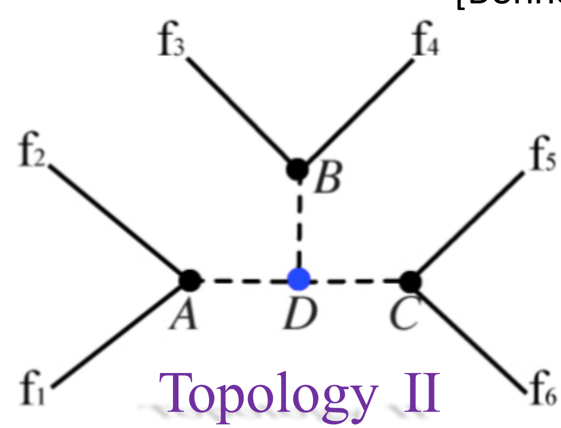
If observed, regardless of the mechanism causing it, the ν has a Majorana mass! [Schechter & Valle, (1982)]

Two topologies of $0\nu\beta\beta$ decay operator

The two basic tree-level topologies realizing [***d***]=***9*** *$0\nu\beta\beta$ decay operator:*

[Bonnet et al (2013)]





v *F*

long-range / short-range

short-range

Outline

- Use “minimal” models: the new interactions respect SM gauge symmetry and are also renormalizable ([d]=3, 4).

- Add new scalars and vectors, and study B and/or L violations.

- We remove proton (p) decay ($|\Delta B| = 1$) explicitly.
  - Non-observation of proton (p) decay set severe constraints on new physics (GUT scale);
  - Lack of “secret ingredients”, such as discrete symmetry, etc. as would appear in a GUT

- We check what mechanisms (models) of $0\nu\beta\beta$ decay can survive.

Eliminate new particles that generate p ($|\Delta B|=1$) decay

Possible interactions between new particles and SM fermions permit no proton decay

- e.g., Xee, VLe, Xud, $X\bar{u}\bar{e}$, XQQ, …

More precisely, e.g., VLe and Xee:

$$g^{ab} V_{3\mu} L^a \sigma^\mu e^b, \quad g_1^{ab} X_1 (e^a e^b)$$

(a and b denote generation.)

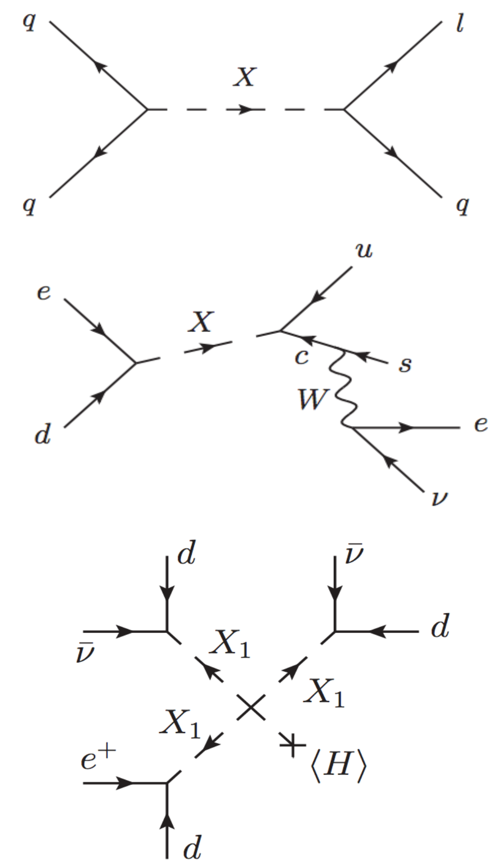
- Note: the representations of new scalars and vectors are in $SU(3)\times SU(2)\times U(1)$

$X(3,1,\text{-}4/3)$, Xuu, $X\bar{d}\bar{e}$

At low E

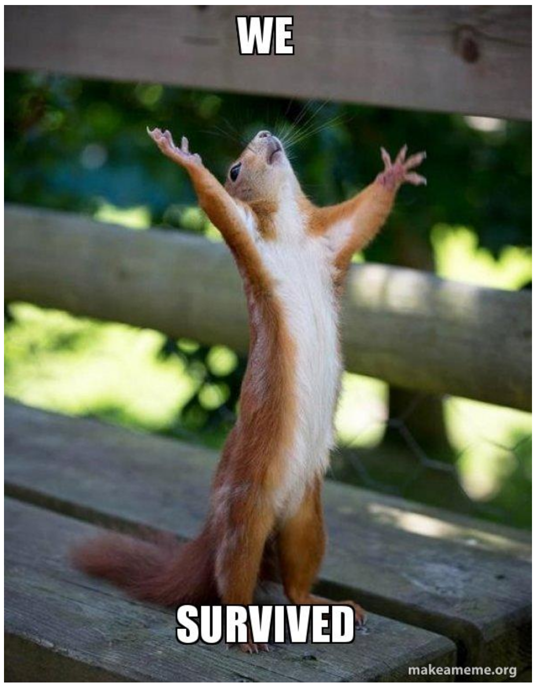
$$\mathcal{L} = udue \Rightarrow p \to e^+ \pi^0$$

Tree level proton decay diagrams



[Arnold, Fornal, and Wise (2013)]

Scalar/vector-fermion interactions without p-decay



Possible interactions between new particles and SM fermions:

Vector	operator	Scalar	operator
$V_1(1,1,0)$	$V\bar{L}L$, $V\bar{e}e$	$X_1(1,1,2)$	Xee
$V_2(1,3,0)$	$V\bar{L}L$	$X_2(1,1,1)$	XLL
$V_3(1,2,\frac{3}{2})$	VLe	$X_3(1,3,1)$	XLL
$V_4(\bar{6},2,-\frac{5}{6})$	VQu	$X_4(\bar{6},3,-\frac{1}{3})$	XQQ
$V_5(\bar{6},2,\frac{1}{6})$	VQd	$X_5(\bar{6},1,-\frac{1}{3})$	XQQ, Xud
$V_1(1,1,0)$	$V\bar{Q}Q$, $V\bar{u}u$,$V\bar{d}d$	$X_6(3,1,\frac{2}{3})$	Xdd
$V_6(1,3,0)$	$V\bar{Q}Q$	$X_7(\bar{6},1,\frac{2}{3})$	Xdd
$V_7(1,1,1)$	$V\bar{u}d$	$X_8(\bar{6},1,-\frac{4}{3})$	Xuu
$V_8(3,1,\frac{2}{3})$	$V\bar{Q}L$,$V\bar{d}e$	$X_9(3,2,\frac{7}{6})$	$X\bar{Q}e$, $XL\bar{u}$
$V_9(3,3,\frac{2}{3})$	$V\bar{Q}L$		
$V_{10}(3,1,\frac{5}{3})$	$V\bar{u}e$		

[Arnold, Fornal, and Wise (2013)
Assad, Fornal, Grinstein (2018)
S. Gardner and X. Y. (2018)]

These interactions do not break L or B!

$0\nu\beta\beta$ decay in minimal ***scalar*** models

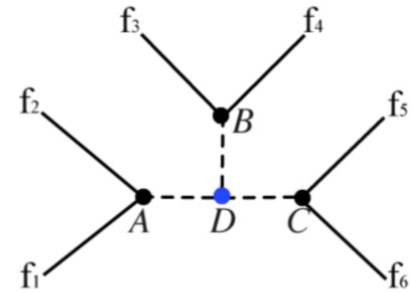
- **Note the different shorthand:** $U_{em}(1)\times SU_c(3)$
- With p decay

#	Decomposition	Mediator (Q_{em}, Q_{colour}) S or V_ρ	S' or V'_ρ	S'' or V''_ρ	Models/Refs./Comments
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	$(+1,\mathbf{1})$	$(+1,\mathbf{1})$	$(-2,\mathbf{1})$	Addl. triplet scalar [69]
					LR-symmetric models [40, 42]
		$(+1,\mathbf{8})$	$(+1,\mathbf{8})$	$(-2,\mathbf{1})$	
2	$(\bar{u}d)(\bar{u}\bar{e})(\bar{e}d)$	$(+1,\mathbf{1})$	$(-1/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	
		$(+1,\mathbf{8})$	$(-1/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	$(+4/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	$(-2,\mathbf{1})$	only with V_ρ and V'_ρ
		$(+4/3,\mathbf{6})$	$(+2/3,\overline{\mathbf{6}})$	$(-2,\mathbf{1})$	
4	$(\bar{u}\bar{u})(\bar{e}d)(\bar{e}d)$	$(+4/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ
		$(+4/3,\mathbf{6})$	$(-2/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	$(-1/3,\mathbf{3})$	$(-1/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V''_ρ
		$(-1/3,\mathbf{3})$	$(-1/3,\mathbf{3})$	$(+2/3,\overline{\mathbf{6}})$	[70, 71]

[Bonnet et al (2013)]

One example:

$X(3,1,\text{-}4/3)$, Xuu is eliminated by no-proton decay condition.



Topology II:

❖ Without p decay

#	Decomposition	S	S'	S''
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	$(-4/3,\bar{6})$	$(+2/3,\bar{6})$	$(+2,1)$

Possible interactions (at D) in SM rep.:

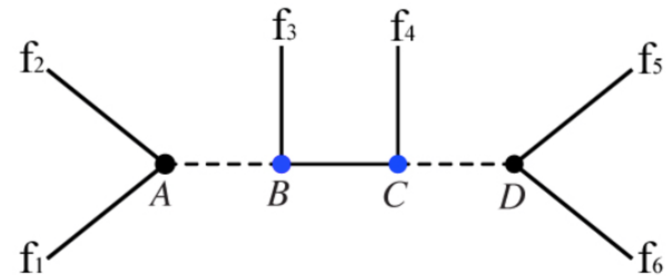
- $X_1X_8X_7^+$
- $X_3X_4X_7^+$
- $X_3X_8X_4^+$

[S. Gardner and X. Y. (2018)]

5→ 1: Number of decompositions drops!!

$0\nu\beta\beta$ decay in minimal *scalar* models

The number of decomposition for topology (I) drops : 18 → 5!



Topology I:

❖ Without p decay

#	Decomposition	S	ψ	S'
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(-4/3, \bar{6})$	$(+1/3, 6)$	$(+2/3, \bar{6})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(-4/3, \bar{6})$	$(+5/3, 3)$	$(+2, 1)$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \bar{6})$	$(+4/3, \bar{3})$	$(+2, 1)$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(-4/3, \bar{6})$	$(+5/3, 3)$	$(+2/3, 3)$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(-4/3, \bar{6})$	$(+1/3, 6)$	$(+2/3, 3)$

[S. Gardner and X. Y. (2018)]

Possible interactions at A, B, C, D in SM rep.:

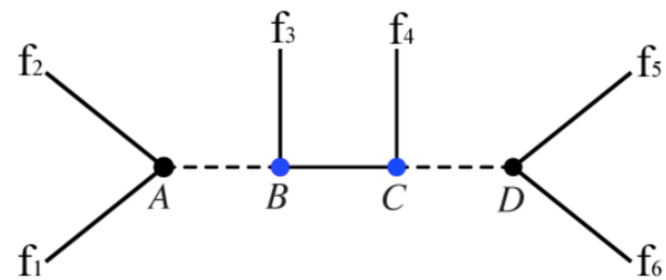
❑ **e.g., 4-ii-a:**

$$X_8^* \bar{u}\bar{u}, \quad X_8 \psi d_R, \quad X_9 \bar{\psi} \bar{e}_L, \quad X_9^* Q \bar{e}, \quad \text{with } \psi = (3, 1, \frac{5}{3})$$

❖ X_i denotes a new scalar.

$0\nu\beta\beta$ decay in minimal *vector* models

- **The number of decomposition for topology (II) drops: 5 → 0!**
- **The number of decomposition for topology (I) drops: 18 → 11!**



Topology I:

Observation:

- **No-p decay has great impact on mechanisms of $0\nu\beta\beta$ decay in both topologies.**
- **We explore possible connection between patterns of |ΔB|=2 process and $0\nu\beta\beta$ decay within minimal *scalar* models in topology (II).**

Possible interactions at A, B, C, D :

- E.g., **4-ii-a**:

$$V_4^* \bar{Q}\bar{\sigma}\bar{u}, \quad V_4 \psi d_R, \quad V_9 \bar{\psi} \bar{e}_L, \quad V_9^* d_L \bar{\sigma} \bar{e}_L \Rightarrow \psi = (3, 2, 7/6)$$

- V_i denotes a new vector.

Minimal scalar X_i interactions that break B and/or L

Topology II:

[S. Gardner and X. Y. (2018)]

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	$X_4X_7X_7X_3^\dagger$

$n-\bar{n}$ oscillation (M1–M3)

dinucleon decay (M5–M9)

conversion (M10–M18)

E.g. : $e^-p \to e^+\bar{p}$

[d]=3, 4.

Appeared in [Arnold, Fornal, and Wise (2013)]

$|\Delta L| = 2, |\Delta B| = 0$

A,B,C => $0\nu\beta\beta$ decay

Patterns of |ΔB|=2 & Majorana neutrino

Model	$n\bar{n}$?	$e^-n \to e^-\bar{n}$?	$e^-p \to \bar{\nu}_X\bar{n}$?	$e^-p \to e^+\bar{p}$?	$0\nu\beta\beta$?
M3	Y	N	N	Y	Y [A]
M2	Y	Y	Y	Y	Y [B]
M1	Y	Y	Y	N	? [D]
–	N	N	Y	Y	? [C?]

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

One example: ***No*** $e^-n \to e^-\bar{n}$ & ***Yes*** $n\bar{n}$,

- M3 has scalar content X_7 and X_8 ;
- $e^-p \to e^+\bar{p}$ only => M10, M12, or M15. Common scalar content: X_1

M3	$X_7X_7X_8$	M10	$X_7X_8X_8X_1$
		M12	$X_5X_5X_8X_1$
A	$X_1X_8X_7^\dagger$	M15	$X_4X_4X_8X_1$

⇨ A ⇨ $\pi^-\pi^- \to e^-e^-$ decay

[S. Gardner and X. Y. (2018)]

"Everything not forbidden is compulsory."

Gell-Mann quotes it from T. H. White

Summary

- We revisit d=9 $0\upsilon\beta\beta$ decay operators and explore their minimal ultraviolet-complete models with new scalars and vectors.

- No proton decay condition eliminates many of the mechanisms of $0\nu\beta\beta$ decay, especially in topology II. Only one survives in scalar models (in the (SU(3), $U(1)_{em}$) basis), and none in vector models.

- Within topology II scalar models, we show that the observation of $n\bar{n}$ oscillations and of particular nucleon-antinucleon conversion processes can reveal the Majorana nature of the neutrino.

Backup Slides

➢ **With p decay**

Topology I:

#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,1)$	$(0,1)$	$(-1,1)$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1,8)$	$(0,8)$	$(-1,8)$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,1)$	$(+5/3,3)$	$(+2,1)$	
			$(+1,8)$	$(+5/3,3)$	$(+2,1)$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,1)$	$(+4/3,\overline{3})$	$(+2,1)$	
			$(+1,8)$	$(+4/3,\overline{3})$	$(+2,1)$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,1)$	$(+4/3,\overline{3})$	$(+1/3,\overline{3})$	
			$(+1,8)$	$(+4/3,\overline{3})$	$(+1/3,\overline{3})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,1)$	$(0,1)$	$(+1/3,\overline{3})$	RPV [58–60], LQ [65, 66]
			$(+1,8)$	$(0,8)$	$(+1/3,\overline{3})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1,1)$	$(+5/3,3)$	$(+2/3,3)$	
			$(+1,8)$	$(+5/3,3)$	$(+2/3,3)$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1,1)$	$(0,1)$	$(+2/3,3)$	RPV [58–60], LQ [65, 66]
			$(+1,8)$	$(0,8)$	$(+2/3,3)$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{3})$	$(0,1)$	$(+1/3,\overline{3})$	RPV [58–60]
			$(-2/3,\overline{3})$	$(0,8)$	$(+1/3,\overline{3})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3,\overline{3})$	$(-1/3,3)$	$(+1/3,\overline{3})$	
			$(-2/3,\overline{3})$	$(-1/3,\overline{6})$	$(+1/3,\overline{3})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3,\overline{3})$	$(+1/3,\overline{3})$	$(-2/3,\overline{3})$	only with V_ρ and V'_ρ
			$(+4/3,6)$	$(+1/3,6)$	$(-2/3,6)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3,\overline{3})$	$(+5/3,3)$	$(+2,1)$	only with V_ρ
			$(+4/3,6)$	$(+5/3,3)$	$(+2,1)$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3,3)$	$(+4/3,\overline{3})$	$(+2,1)$	only with V_ρ
			$(+2/3,\overline{6})$	$(+4/3,\overline{3})$	$(+2,1)$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3,\overline{3})$	$(0,1)$	$(+2/3,3)$	RPV [58–60]
			$(-2/3,\overline{3})$	$(0,8)$	$(+2/3,3)$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3,\overline{3})$	$(+5/3,3)$	$(+2/3,3)$	only with V_ρ
			$(+4/3,6)$	$(+5/3,3)$	$(+2/3,3)$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3,\overline{3})$	$(+1/3,\overline{3})$	$(+2/3,3)$	only with V_ρ
			$(+4/3,6)$	$(+1/3,6)$	$(+2/3,3)$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3,3)$	$(0,1)$	$(+1/3,\overline{3})$	RPV [58–60]
			$(-1/3,3)$	$(0,8)$	$(+1/3,\overline{3})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3,3)$	$(+1/3,\overline{3})$	$(-2/3,\overline{3})$	only with V'_ρ
			$(-1/3,3)$	$(+1/3,6)$	$(-2/3,6)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3,3)$	$(-4/3,3)$	$(-2/3,\overline{3})$	only with V'_ρ
			$(-1/3,3)$	$(-4/3,3)$	$(-2/3,6)$	

[Bonnet et al (2013)]

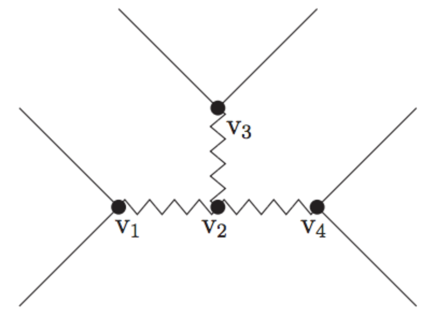
$0\nu\beta\beta$ decay in minimal scalar-vector models

With p decay

Topology II:

[Bonnet et al (2013)]

#	Decomposition	Mediator $(Q_{\rm em}, Q_{\rm colour})$ S or V_ρ	S' or V'_ρ	S'' or V''_ρ	Models/Refs./Comments
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	$(+1, \mathbf{1})$	$(+1, \mathbf{1})$	$(-2, \mathbf{1})$	Addl. triplet scalar [69]
					LR-symmetric models [40, 42]
		$(+1, \mathbf{8})$	$(+1, \mathbf{8})$	$(-2, \mathbf{1})$	
2	$(\bar{u}d)(\bar{u}\bar{e})(\bar{e}d)$	$(+1, \mathbf{1})$	$(-1/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}})$	
		$(+1, \mathbf{8})$	$(-1/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}})$	
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}})$	$(+2/3, \mathbf{3})$	$(-2, \mathbf{1})$	only with V_ρ and V'_ρ
		$(+4/3, \mathbf{6})$	$(+2/3, \overline{\mathbf{6}})$	$(-2, \mathbf{1})$	
4	$(\bar{u}\bar{u})(\bar{e}d)(\bar{e}d)$	$(+4/3, \overline{\mathbf{3}})$	$(-2/3, \overline{\mathbf{3}})$	$(-2/3, \overline{\mathbf{3}})$	only with V_ρ
		$(+4/3, \mathbf{6})$	$(-2/3, \overline{\mathbf{3}})$	$(-2/3, \overline{\mathbf{3}})$	
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(-1/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	only with V''_ρ
		$(-1/3, \mathbf{3})$	$(-1/3, \mathbf{3})$	$(+2/3, \overline{\mathbf{6}})$	[70, 71]



Topology II

Without p decay

Surviving decomposition & possible models:

#	Decomposition	S or V	S' or V'	S'' or V''
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	$(1, 1)$	$(1, 1)$	$(2, 1)$
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	$(-4/3, \bar{6})$	$(+2/3, \bar{6})$	$(+2, 1)$
4	$(\bar{u}\bar{u})(\bar{e}d)(\bar{e}d)$	$(-4/3, \bar{6})$	$(+2/3, 3)$	$(+2/3, 3)$

- **#1:** $V_7^\mu V_{7\mu} X_1^+$, $V_6^\mu V_{7\mu} X_3^+$
- **#3:** $V_4^\mu V_{5\mu}^+ X_3$, $V_3^\mu V_{5\mu}^+ X_8$, $V_4^\mu V_{3\mu} X_7^+$, $X_1 X_8 X_7^+$, $X_3 X_4 X_7^+$, $X_3 X_8 X_4^+$
- **#4:** $V_9^\mu V_{9\mu} X_8$

[Susan Gardner and X. Y. (2018)]

$0\nu\beta\beta$ decay in minimal scalar-vector models

❖ Without p decay

Topology I:

#	Decomposition	S or V	ψ	S' or V'
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(1,1)$	$(0,1)$	$(1,1)$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(1,1)$	$(+5/3,3)$	$(+2,1)$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(1,1)$	$(+4/3,\bar{3})$	$(+2,1)$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(1,1)$	$(+5/3,3)$	$(+2/3,3)$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(1,1)$	$(0,1)$	$(+2/3,3)$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(-3/4,\bar{6})$	$(+1/3,6)$	$(+2/3,\bar{6})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(-3/4,\bar{6})$	$(+5/3,3)$	$(+2,1)$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3,\bar{6})$	$(+4/3,\bar{3})$	$(+2,1)$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(+2/3,3)$	$(0,1)$	$(+2/3,3)$
		$(+2/3,3)$	$(0,8)$	$(+2/3,3)$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(-3/4,\bar{6})$	$(+5/3,3)$	$(+2/3,3)$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(-3/4,\bar{6})$	$(+1/3,6)$	$(+2/3,3)$

1-i → V–ψ–V

1-ii-a, 1-ii-b, 2-ii-a, 2-ii-b → V–ψ–V, V–ψ–S

3-i, 3-ii, 3-iii → V–ψ–V, V–ψ–S, S–ψ–V, S–ψ–S

4-i → V–ψ–V

4-ii-a → V–ψ–V, S–ψ–V, S–ψ–S

4-ii-b → S–ψ–V, S–ψ–S

[S. Gardner and X. Y. (2018)]

Quark level $n - \bar{n}$ oscillation

- There are 4 independent quark level $n - \bar{n}$ oscillation operators that respect SM gauge symmetry:

$$(O_1)_{RRR},\ (O_2)_{RRR},\ (O_3)_{LRR},\ (O_3)_{LLR}$$

[Rao and Shrock (1982)
W. Caswell et al (1983)
M. Buchoff et al (2012)]

- Note: M1 yields the operator $(\mathcal{O}_2)_{\rm RRR}$, M2 yields $(\mathcal{O}_3)_{\rm LLR}$, M3 yields $(\mathcal{O}_1)_{\rm RRR}$.

Quark level $n - \bar{n}$ oscillation operators with $SU(3)\otimes U_{em}(1)$.

$$\begin{aligned}
(O_1)_{\chi_1\chi_2\chi_3} &= [u_{\chi_1}^{\top\alpha} C u_{\chi_1}^{\beta}][d_{\chi_2}^{\top\gamma} C d_{\chi_2}^{\delta}][d_{\chi_3}^{\top\rho} C d_{\chi_3}^{\sigma}](T_s)_{\alpha\beta\gamma\delta\rho\sigma},\\
(O_2)_{\chi_1\chi_2\chi_3} &= [u_{\chi_1}^{\top\alpha} C d_{\chi_1}^{\beta}][u_{\chi_2}^{\top\gamma} C d_{\chi_2}^{\delta}][d_{\chi_3}^{\top\rho} C d_{\chi_3}^{\sigma}](T_s)_{\alpha\beta\gamma\delta\rho\sigma},\\
(O_3)_{\chi_1\chi_2\chi_3} &= [u_{\chi_1}^{\top\alpha} C d_{\chi_1}^{\beta}][u_{\chi_2}^{\top\gamma} C d_{\chi_2}^{\delta}][d_{\chi_3}^{\top\rho} C d_{\chi_3}^{\sigma}](T_a)_{\alpha\beta\gamma\delta\rho\sigma},
\end{aligned}$$

$$(T_s)_{\alpha\beta\gamma\delta\rho\sigma} = \epsilon_{\rho\alpha\gamma}\epsilon_{\sigma\beta\delta} + \epsilon_{\sigma\alpha\gamma}\epsilon_{\rho\beta\delta} + \epsilon_{\rho\beta\gamma}\epsilon_{\sigma\alpha\delta} + \epsilon_{\sigma\beta\gamma}\epsilon_{\rho\alpha\delta}$$
$$(T_a)_{\alpha\beta\gamma\delta\rho\sigma} = \epsilon_{\rho\alpha\beta}\epsilon_{\sigma\gamma\delta} + \epsilon_{\sigma\alpha\beta}\epsilon_{\rho\gamma\delta}.$$

[Rao and Shrock (1982)]

Cross Section Estimate

Experimental limits can be translated to scalar-mass-coupling exclusion plots (cf. dark photons!)

scalar couplings [4, 56–59]. Models that support $e^- p \to e^+ \bar{p}$ 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 [60, 61] computation of $\langle \bar{n} | (\mathcal{O}_1)_{RRR} | n \rangle$ [46, 62] yields

$$\sigma \sim 1.5 \times 10^{-5} (g_7^{11})^6 (\lambda_8 g_1^{11})^2 \left(\frac{5\,\mathrm{GeV}}{M_{X_7}} \right)^{12} \left(\frac{1\,\mathrm{GeV}}{M_{X_1}} \right)^4 \mathrm{ab} \quad (6)$$

in model M8 for an electron beam energy of 155 MeV with a fixed target [63]. A broad range of possible scalar masses and couplings exists.

[SG & Xinshuai Yan, arXiv: 1808.05288]

Estimate event number

Fixed target experiment:

$$\frac{dN}{dt} = \mathcal{L}\sigma = \phi\rho_T L\sigma$$

$$N \sim 1.4 \times 10^2 \frac{\mathrm{t}}{1\ \mathrm{yr}} \frac{\phi}{0.6 \times 10^{17}\ \mathrm{s}^{-1}} \frac{L}{1\ \mathrm{m}} \frac{\rho}{5.1 \times 10^{22}\ \mathrm{cm}^{-3}} \frac{\sigma}{1.5 \times 10^{-5}\ \mathrm{ab}}.$$

- t denotes experiment running time, L is the length of liquid deuterium target at 19K with number density ρ.
- ϕ is the flux of electron beam(Dark Light exp. at Jlab)

Dim 5 and 7 proton decay

Operator	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	p decay
$\overline{Q}^c_L \gamma^\mu u_R V_\mu$	3	2	$-5/6$	tree-level
	$\bar{6}$	2	$-5/6$	–
$\overline{Q}^c_L \gamma^\mu d_R V_\mu$	3	2	$1/6$	tree-level
	$\bar{6}$	2	$1/6$	–
$\overline{Q}_L \gamma^\mu L_L V_\mu$	3	1, 3	$2/3$	dim 5
$\overline{Q}^c_L \gamma^\mu e_R V^*_\mu$	3	2	$-5/6$	tree-level
$\overline{L}^c_L \gamma^\mu u_R V^*_\mu$	3	2	$1/6$	tree-level
$\overline{L}^c_L \gamma^\mu d_R V^*_\mu$	3	2	$-5/6$	tree-level
$\overline{u}_R \gamma^\mu e_R V_\mu$	3	1	$5/3$	dim 7
$\overline{d}_R \gamma^\mu e_R V_\mu$	3	1	$2/3$	dim 5

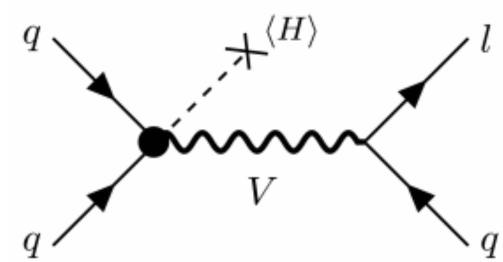


FIG. 2. Proton decay through a dimension five interaction for $V = (3,1)_{\frac{2}{3}}$ and $V = (3,3)_{\frac{2}{3}}$.

Assad, Fornal, Grinstein (2018)