Determining the Majorana nature of neutrino through patterns of $|\Delta B|=2$ processes

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Based on two papers in collaboration with Susan Gardner:
[S.Gardner and X.Y., arXiv:1808.05288 and PRD 97 056008 (2018) arXiv:1710.09292]

B-L violation

- In the Standard Model (SM), neither baryon number (B) nor lepton number (L) is conserved, but B-L is. Thus the observation of B-L violation reveal the existence of physics BSM.

B-L violation:

- In lepton sector: Observation of neutrinoless double $(0\upsilon\beta\beta)$ decay shows that L is broken by two units. That is to say that neutrino has an effective Majorana mass.

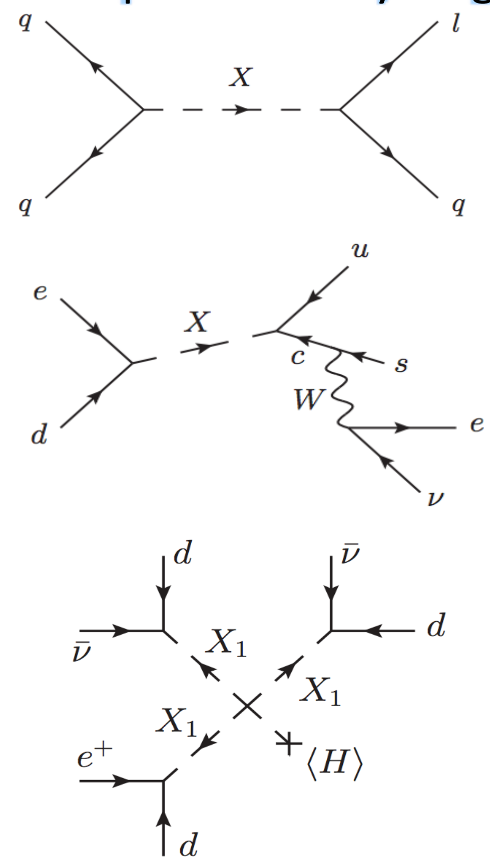
[J. Schechter and J. W. Valle (2012)]

- In quark sector:
  - Neutron-antineutron oscillation ---- **Spontaneous**. [Marshak and Mohapatra (1980)]
  - Dinucleon decay (in nuclei) --- limited by finite nuclei density.
  - Nucleon-antinucleon conversion ---- **Mediated by an external source**.

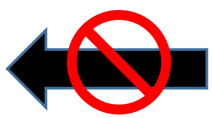
[Susan Gardner and X. Y., PRD (2018)]

Scalar-fermion interactions with no proton decay

Tree level proton decay diagrams



[Arnold, Fornal, and Wise (2013)]



Possible interactions between scalar particle X and SM fermions:

Scalar	SM Representation	B	L	Operator(s)	$[g_i^{ab}?]$
X_1	$(1,1,2)$	0	-2	Xe^ae^b	[S]
X_2	$(1,1,1)$	0	-2	XL^aL^b	[A]
X_3	$(1,3,1)$	0	-2	XL^aL^b	[S]
X_4	$(\bar{6},3,-1/3)$	-2/3	0	XQ^aQ^b	[S]
X_5	$(\bar{6},1,-1/3)$	-2/3	0	XQ^aQ^b, Xu^ad^b	[A,–]
X_6	$(3,1,2/3)$	-2/3	0	Xd^ad^b	[A]
X_7	$(\bar{6},1,2/3)$	-2/3	0	Xd^ad^b	[S]
X_8	$(\bar{6},1,-4/3)$	-2/3	0	Xu^au^b	[S]
X_9	$(3,2,7/6)$	1/3	-1	$X\bar{Q}^ae^b, XL^a\bar{u}^b$	[–,–]

E.g., $g_1^{ab}X_1(e^ae^b)$

[Arnold, Fornal, and Wise (2013)
Susan Gardner and X. Y. (2018)]

Note these interactions do not break B and L !

Minimal interactions that break B and/or L

[Susan 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)

nucleon − antinucleon conversion (M5–M9)

New conversion (M10–M18)

$|\Delta L| = 2, |\Delta B| = 0$ (A–G)

Appeared in [Arnold, Fornal, and Wise (2013)] (M1–M9)

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 $(\mathcal{O}_1)_{\rm RRR}$.

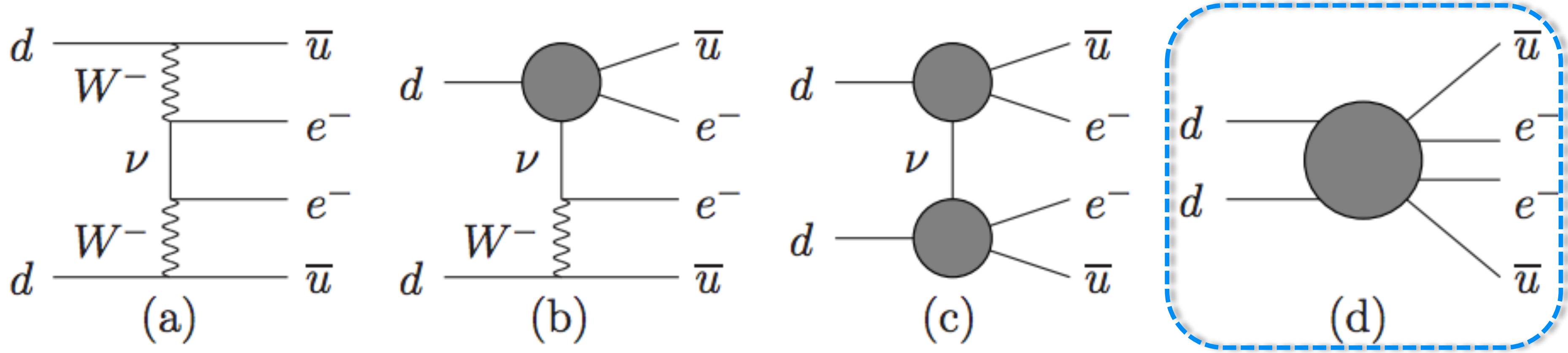
Quark level $n-\bar{n}$ oscillation operators with SU(3)⊗$U_{em}(1)$.

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

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

[Rao and Shrock (1982)]

Mechanisms of $0\upsilon\beta\beta$ decay



[Bonnet et al (2013)]

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

Only models A, B, and C can produce $\pi^-\pi^- \rightarrow e^-e^-$ decay, which correspond to the second case of decay topology "T-II-3" in Bonnet et al (2013).

Processes of interest generated by the models

We list the $|\Delta L| = 2$ and $|\Delta B| = 2$ processes generated by the models in which only first-generation fermion are involved.

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

(*) indicates that a weak isospin triplet of $|\Delta L| = 2$ processes can appear.

Patterns of |ΔB|=2 & Majorana neutrino

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

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?]

- We have showed that $e^-n \to e^-\bar{n}$ can not appear if $n - \bar{n}$ oscillation is mediated through $(\mathcal{O}_1)_{RRR.}$ ➡ Distinguish M3 from M1 and M2

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

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	$X_4X_4X_8X_1$

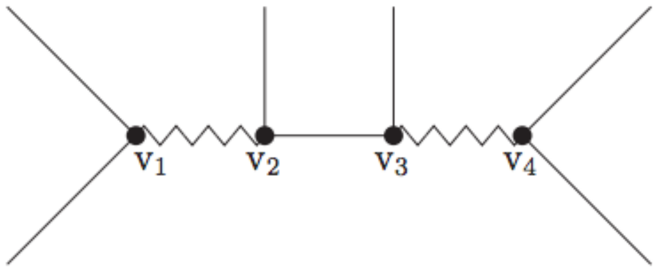
➡ A ➡ $\pi^-\pi^- \to e^-e^-$ decay

Summary

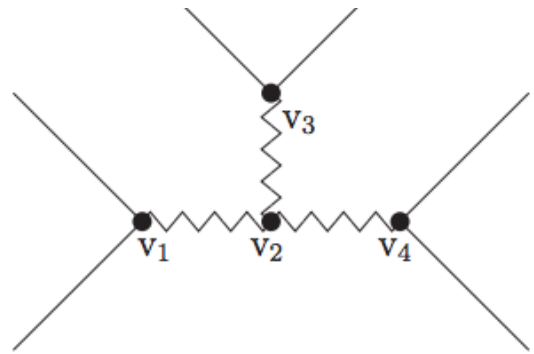
- Motivated by search for new physics, we explore simple BSM scalar models with B, L, and B-L violation. For phenomenological viability, we permit no proton decay for these models.
- Various $|\Delta B| = 2$ and $|\Delta L| = 2$ processes, such as $n\bar{n}$ oscillation and nucleon-antinucleon conversion and $0\upsilon\beta\beta$ decay, can be studied within these 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

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



Topology I



Topology II

		Mediator $(Q_{\rm em}, Q_{\rm colour})$			
#	Decomposition	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)]

Simple BSM scalar models with no proton decay

Develop simple models with new scalar gauge bosons whose interactions:

- Respect SU(3) X SU(2) X U(1) symmetry ---- SM symmetry;
- Have mass dimension 3 and 4 ---- Renormalizable;
- Break B or/and L;
- Do not permit proton decay at tree level;

and study their various phenomenology.

Proton decay:

- Has never been observed!
- Impose severe constraints on new physics, e.g., proton life time for $p \to e^+ \pi^0$ mode 8.2 X 10^{33} yr. [H. Nishino et al. (Super-K) (2009)]

This talk is based on two papers in collaboration with Susan Gardner:

[S.Gardner and X.Y **arXiv:1808.05288**, **PRD 97 056008** (2018)]

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]