The left-right handed asymmetric weak boson exchange in neutrinoless double beta decay

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Ref.)

D. Stefanik, R. Dvornicky, F. Simkovic, P. Vogel, Phys. Rev. C92 (2015) 055502.

F. Simkovic, D. Stefanik, R. Dvornicky, Front. Phys. (2017) 5:57.

S. Sarkar, Y. Iwata, P. K. Raina, Phys. Rev. C102 (2020) 034317.

Verdados, Ejiri, et al. Prog. Phys. C 2012

Y. Iwata, S. Sarkar, in preparation.

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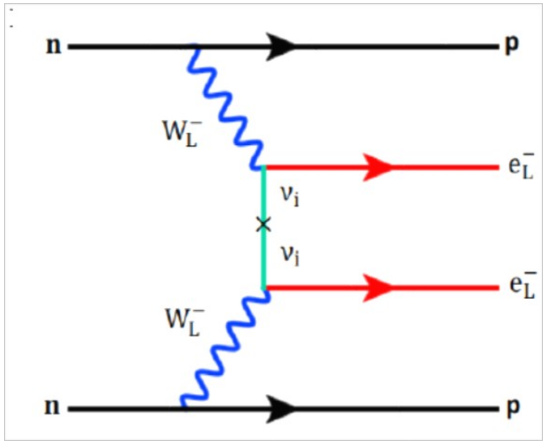
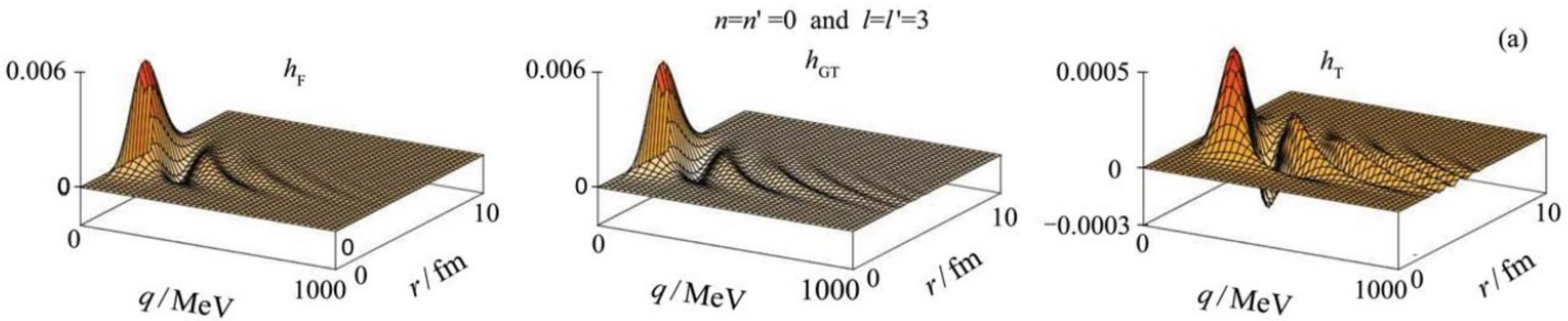




Neutrino potential
Y. I., Nucl. Phys. Rev. 2017

Half-life & nuclear matrix element (NME)

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q,Z)g_A^4|M^{0\nu}|^2\frac{|m_{\beta\beta}|^2}{m_e^2}$$

Inverse of Half life

Axial vector current coupling constant

The left-right symmetric theory

m_e :electron mass

Effective Majorana neutrino mass

$$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3$$

Uei : Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix

Theoretical methods
nuclear matrix element (NME)

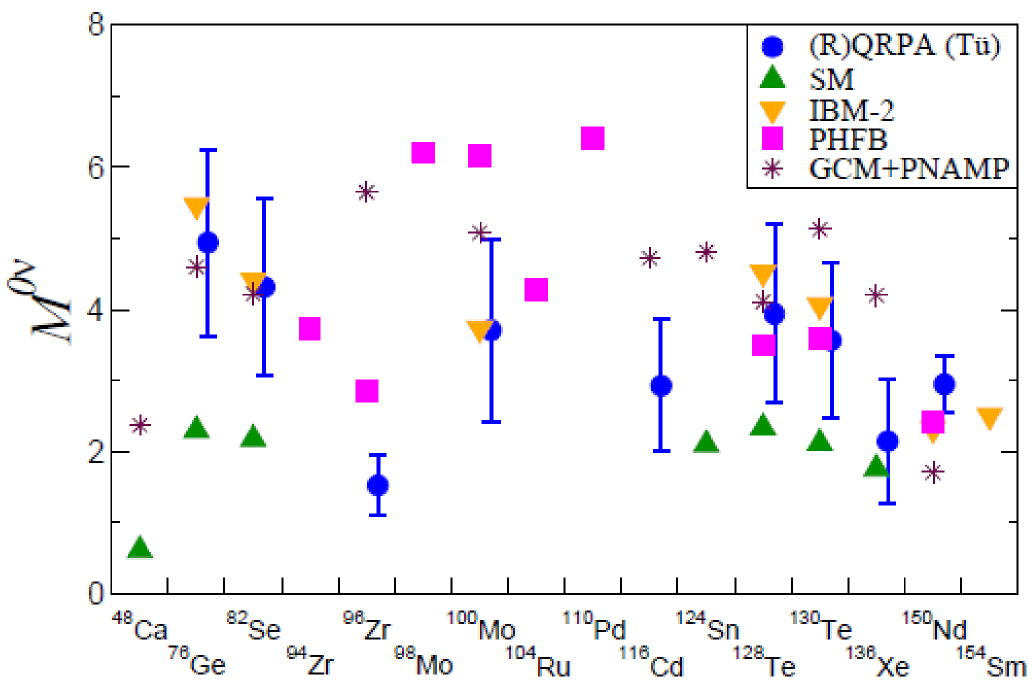
ISM （Interacting shell model）

IBM（Interacting boson model）

QRPA （random phase approximation）

HFB, EDF (Hartree-Fock Bogoliubov)

GCM（Generator coordinate method）



Feassler, J. Phys. Conf. Ser. 2012.

WL-WL and light neutrinos are taken into account

λ mechanism

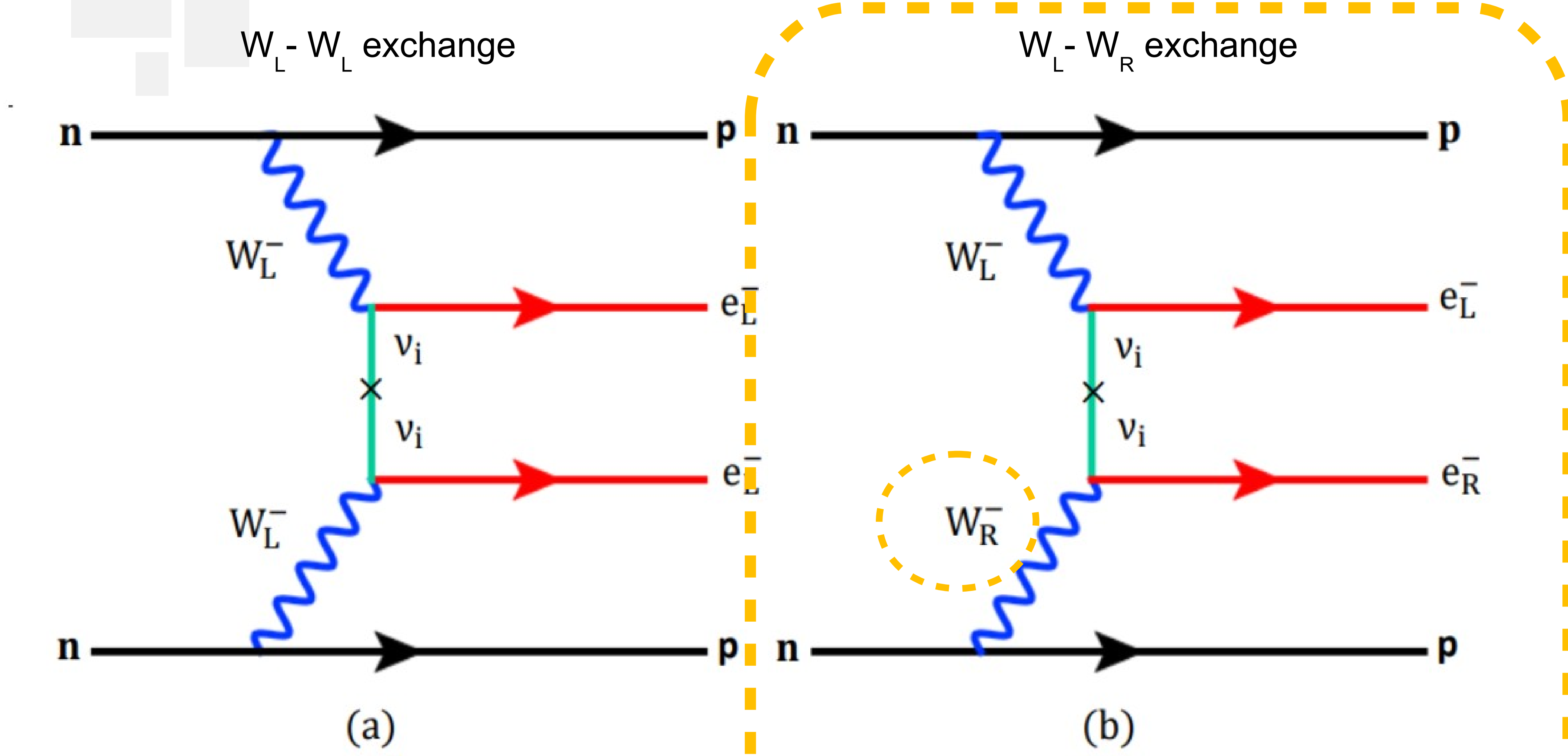


FIG. 1. (Color online) The Feynman diagrams for $0\nu\beta\beta$ via (a) $W_L - W_L$ mediation ($m_{\beta\beta}$ mechanism) and (b) $W_L - W_R$ mediation (λ mechanism) with light neutrinos exchange.

λ mechanism

PHYSICAL REVIEW C **92**, 055502 (2015)

Reexamining the light neutrino exchange mechanism of the $0\nu\beta\beta$ decay with left- and right-handed leptonic and hadronic currents

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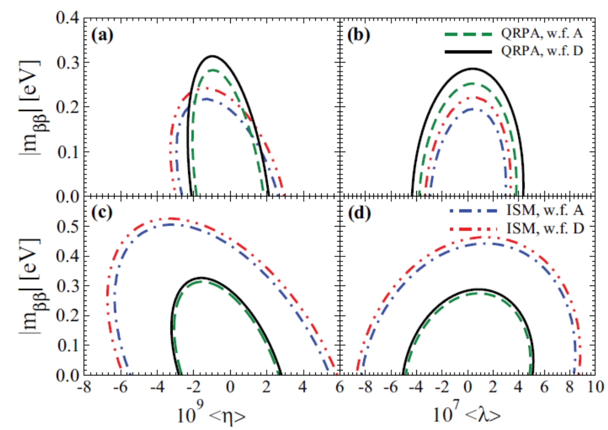
Left-right symmetric model

- *WL*-*WR* exchange (λ mechanism)
- *WL*-*WR* mixing (η mechanism)



Limits on the effective neutrino mass $m_{\beta\beta}$

Starting point of the recent r-handed works in DBD

Left right symmetric model

J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974)
R. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 2558 (1975).
G. Senjanovic and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett.**44**, 912 (1980); Phys. Rev. D **23**, 165 (1981).
V. Khachatryan *et al.* (CMS Collaboration), Eur. Phys. J. C **74**, 3149 (2014).

LHC experiment

$$\begin{pmatrix} W_L^- \\ W_R^- \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^- \\ W_2^- \end{pmatrix}$$

$$M_{W1} < M_{W2}$$

$$SU(2)_L \otimes \boxed{SU(2)_R} \otimes \boxed{U(1)_{B-L}}$$

Higgs mechanism

The Higgs sector contains a bidoublet ϕ and two triplets Δ_L and Δ_R with vacuum expectation values (VEVs) v_L and v_R, respectively. The VEVs fulfill the condition $v_L v_R = v^2$. The VEV v_R breaks $SU(2)_R \otimes U(1)_{B-L}$ to $U(1)_Y$ and generates masses for the right-handed W_R and Z_R gauge bosons and the heavy neutrinos.

Leptonic current

$$j_L^\rho = \bar{e}\gamma_\rho(1-\gamma_5)\nu_{eL}, \quad j_R^\rho = \bar{e}\gamma_\rho(1+\gamma_5)\nu_{eR}$$

$$\nu_{eL} = \sum_{j=1}^{3}(U_{ej}\nu_{jL} + S_{ej}(N_{jR})^C),$$

$$\nu_{eR} = \sum_{j=1}^{3}(T_{ej}^*(\nu_{jL})^C + V_{ej}^* N_{jR}).$$

ν_{eL}, ν_{eR}: the weak eigenstate of electron neutrinos

$$\mathcal{U} = \begin{pmatrix} U & S \\ T & V \end{pmatrix} \xrightarrow{\text{diagonalize}} \mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}$$

basis $(\nu_L,(N_R)^C)^T$

Majorana and Diracmass terms

decompose

prop. to Yukawa coupls. $M_L \approx y_M v_L$, $M_R \approx y_M v_R$, and $M_D \approx y_D v$,

$$\mathcal{U} = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & U_0 \end{pmatrix}\begin{pmatrix} A & R \\ S & B \end{pmatrix}\begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}$$

neglecting the mixing between different generations of light and heavy neutrinos.

$$A \approx \mathbf{1}, \quad B \approx \mathbf{1}, \quad R \approx \frac{m_D}{m_{\mathrm{LNV}}}\mathbf{1}, \quad S \approx -\frac{m_D}{m_{\mathrm{LNV}}}\mathbf{1}$$

m_{LNV} is the total lepton number violating scale

Hadronic current (with nonrelativistic assump.)

$$J_L^{\rho\dagger}(\mathbf{x}) = \sum_n \tau_n^+ \delta(\mathbf{x}-\mathbf{r}_n)\Bigg[(g_V - g_A C_n)g^{\rho 0} + g^{\rho k}\left(g_A \sigma_n^k - g_V D_n^k - g_P q_n^k \frac{\vec{\sigma}_n \cdot \mathbf{q}_n}{2m_N}\right)\Bigg],$$

$$J_R^{\rho\dagger}(\mathbf{x}) = \sum_n \tau_n^+ \delta(\mathbf{x}-\mathbf{r}_n)\Bigg[(g'_V + g'_A C_n)g^{\rho 0} + g^{\rho k}\left(-g'_A \sigma_n^k - g'_V D_n^k + g'_P q_n^k \frac{\vec{\sigma}_n \cdot \mathbf{q}_n}{2m_N}\right)\Bigg].$$

$$\mathbf{q}_n = \mathbf{p}_n - \mathbf{p}'_n$$

the momentum transfer between the nucleons

Nucleon recoil operator

$$C_n = \frac{\vec{\sigma}\cdot(\mathbf{p}_n + \mathbf{p}'_n)}{2m_N} - \frac{g_P}{g_A}(E_n - E'_n)\frac{\vec{\sigma}\cdot\mathbf{q}_n}{2m_N},$$

$$\mathbf{D}_n = \frac{(\mathbf{p}_n + \mathbf{p}'_n)}{2m_N} - i\left(1 + \frac{g_M}{g_V}\right)\frac{\vec{\sigma}\times\mathbf{q}_n}{2m_N}.$$

V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, J. High Energy Phys. 12 (2017) 082.

V. Cirigliano, W. Dekens, M. Graesser, and E. Mereghetti, Phys. Lett. B **769**, 460 (2017).

Current-current interaction

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Effective current-current interaction acting on DBD

$$H^\beta = \frac{G_\beta}{\sqrt{2}}[j_L^\rho J_{L\rho}^\dagger + \chi j_L^\rho J_{R\rho}^\dagger + \eta j_R^\rho J_{L\rho}^\dagger + \lambda j_R^\rho J_{R\rho}^\dagger + \text{H.c.}]$$

$$\eta \simeq -\tan\zeta \qquad \lambda \simeq \left(M_{W_1}/M_{W_2}\right)^2$$

$$\chi = \eta$$

$$\boxed{G_\beta = G_F \cos\theta_C}$$

G_F: Fermi const.
θ_c: Cabibo angle

Leptonic current

$$j_L^\rho = \bar{e}\gamma_\rho(1-\gamma_5)\nu_{eL}, \quad j_R^\rho = \bar{e}\gamma_\rho(1+\gamma_5)\nu_{eR}$$

ν_{eL}, ν_{eR}: the weak eigenstate electron neutrinos

Half-life & nuclear matrix element (NME)

in **left-right symmetric model**

$$[T_{1/2}^{0\nu}]^{-1} = \frac{\Gamma^{0\nu}}{\ln 2}$$

Only GT is considered

$$= g_A^4 |M_{GT}|^2 \left\{ C_{mm} \left(\frac{|m_{\beta\beta}|}{m_e} \right)^2 + C_{m\lambda} \frac{|m_{\beta\beta}|}{m_e} \langle\lambda\rangle \cos\psi_1 \right.$$

$$+ C_{m\eta} \frac{|m_{\beta\beta}|}{m_e} \langle\eta\rangle \cos\psi_2 + C_{\lambda\lambda} \langle\lambda\rangle^2 + C_{\eta\eta} \langle\eta\rangle^2$$

$$\left. + C_{\lambda\eta} \langle\lambda\rangle\langle\eta\rangle \cos(\psi_1 - \psi_2) \right\}.$$

To be compared to ...

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q,Z) g_A^4 |M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

Calculation of neutrino pot part

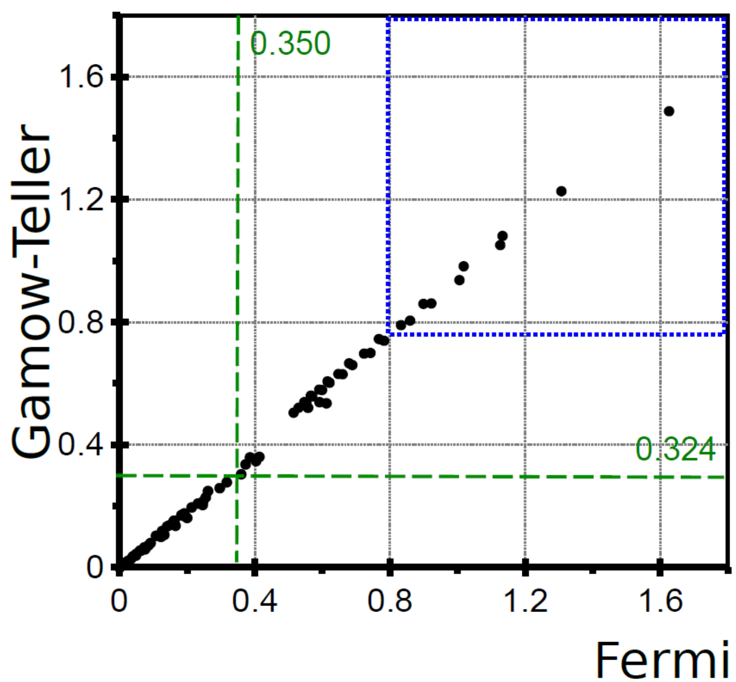
Top 10 amplitude

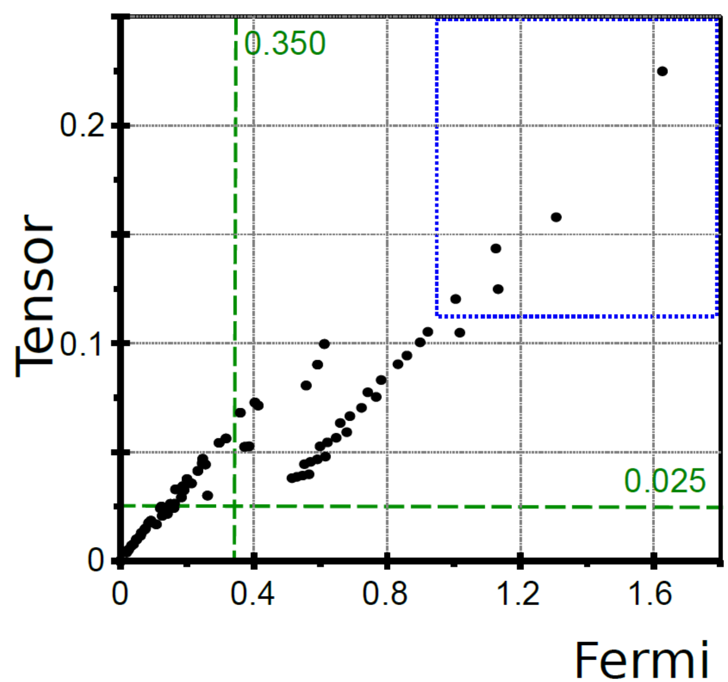
Ranking	Fermi $(n\ l\ n'\ l')$	Value	Gamow-Teller $(n\ l\ n'\ l')$	Value	Tensor $(n\ l\ n'\ l')$	Value
1	(0 0 0 0)	1.626	(0 0 0 0)	1.488	(0 0 0 0)	0.2249
2	(1 0 1 0)	1.307	(1 0 1 0)	1.227	(0 0 0 1) (0 1 0 0)	0.1637
3	(2 0 2 0)	1.133	(2 0 2 0)	1.081	(1 0 1 0)	0.1579
4	(0 1 0 1)	1.126	(0 1 0 1)	1.051	(0 1 0 1)	0.1435
5	(3 0 3 0)	1.018	(3 0 3 0)	0.982	(2 0 2 0)	0.1248
6	(1 1 1 1)	1.006	(1 1 1 1)	0.937	(0 0 1 1) (1 1 0 0)	0.1204
7	(2 1 2 1)	0.922	(2 1 2 1)	0.861	(1 1 1 1)	0.1203
8	(0 2 0 2)	0.899	(0 2 0 2)	0.859	(0 1 0 2) (0 2 0 1)	0.1130
9	(3 1 3 1)	0.859	(3 1 3 1)	0.805	(1 0 1 1) (1 1 1 0)	0.1115
10	(1 2 1 2)	0.836	(1 2 1 2)	0.790	(0 0 0 2) (0 2 0 0)	0.1112

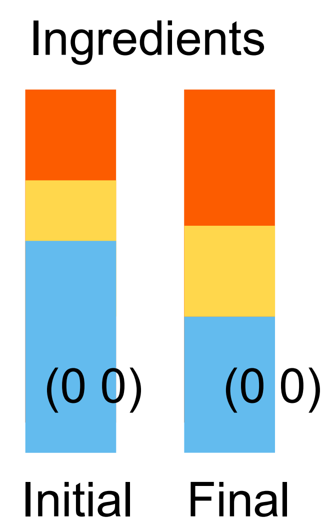
$$H_\alpha(\sqrt{2}\rho) = \frac{2R}{\pi}\int_0^\infty f_\alpha(\sqrt{2}\rho q)\frac{h_{\alpha(q)}}{q+\langle E\rangle}\ q\ dq$$

Closure approx.

$$\sum_{n,n',l,l'} k_{n,n',l,l'}\ \langle \boxed{n'l'} \| H_\alpha(\sqrt{2}\rho) \| \boxed{nl} \rangle$$







Neutrinoless DBD Matrix element

Half life (used in the modern works; ***η* terms are ignored**)

$$[T^{0\nu}_{1/2}]^{-1} = \underline{\eta_\nu^2 C_{mm}} + \boxed{\eta_\lambda^2 C_{\lambda\lambda} + \eta_\nu \eta_\lambda \cos\psi C_{m\lambda}}$$

usual WL-WL exchange

New

[Stefanik 2015]

G_{09}	10^{-9}
G_{08}	10^{-11}
G_{07}	10^{-10}
G_{06}	10^{-12}
G_{05}	10^{-13}
G_{02}	
G_{01}	10^{-14}
G_{10}	
G_{03}	
G_{11}	10^{-15}
G_{04}	

Matrix element

$$C_{mm} = g_A^4 \boxed{M_\nu^2} G_{01},$$

small~1/10 small~1/10

$$C_{m\lambda} = -g_A^4 \boxed{M_\nu}(\boxed{M_{2-}} G_{03} - \boxed{M_{1+}} G_{04})$$

$$C_{\lambda\lambda} = g_A^4 (\boxed{M_{2-}^2} G_{02} + \frac{1}{9}\boxed{M_{1+}^2} G_{011} - \frac{2}{9}\boxed{M_{1+}}\boxed{M_{2-}} G_{010})$$

large~*10 small~1/10 ~*1

accurate G_{0i}: phase space factor (i = 1,2,3, … ,11)

$$g_A = 1.27$$

bare

Effective lepton number violation parameters

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e}, \quad \eta_\lambda = \lambda \left| \sum_{j=1}^{3} m_j U_{ej} T_{ej}^* \right|,$$

$$\psi = \arg\left[\left(\sum_{j=1}^{3} m_j U_{ej}^2 \right) \left(\sum_{j=1}^{3} U_{ej} T_{ej}^* \right) \right]$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

[Simkovic 2017] For Ca,

$$\eta_\nu = 2.23 \times 10^{-5}$$
$$\eta_\lambda = 2.24 \times 10^{-5}$$

Calculation of nuclear matrix element

$$M_\alpha^{0\nu} = \langle f | \tau_{-1}\tau_{-2}\mathcal{O}_{12}^{\alpha} | i \rangle$$

F, GT, T

$$\mathcal{O}_{12}^{GT,\omega GT,qGT} = \tau_{1-}\tau_{2-}(\sigma_1.\sigma_2)H_{GT,\omega GT,qGT}(r,E_k),$$
$$\mathcal{O}_{12}^{F,\omega F,qF} = \tau_{1-}\tau_{2-}H_{F,\omega F,qF}(r,E_k),$$
$$\mathcal{O}_{12}^{T,\omega T,qT} = \tau_{1-}\tau_{2-}S_{12}H_{T,\omega T,qT}(r,E_k),$$

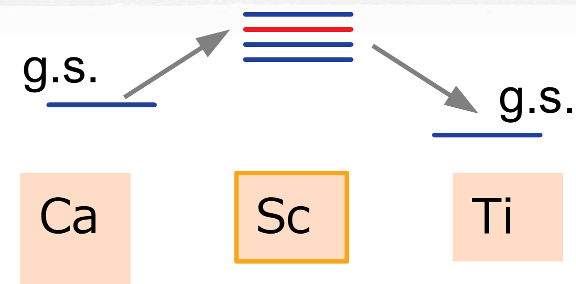
$$S_{12} = 3(\sigma_1.\hat{\mathbf{r}})(\sigma_2.\hat{\mathbf{r}}) - (\sigma_1.\sigma_2), \ \mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$$

$$M_\nu = M_{GT} - \frac{M_F}{g_A^2} + M_T,$$
$$\boxed{M_{\nu\omega}} = M_{\omega GT} - \frac{M_{\omega F}}{g_A^2} + M_{\omega T},$$
$$\boxed{M_{1+}} = M_{qGT} + 3\frac{M_{qF}}{g_A^2} - 6M_{qT},$$
$$M_{2-} = \boxed{M_{\nu\omega}} - \frac{1}{9}\boxed{M_{1+}}$$

$$H_\alpha(r,E_k) = \frac{2R}{\pi}\int_0^\infty \frac{f_\alpha(q,r)qdq}{q+E_k-(E_i+E_f)/2}$$

Included:
finite nucleon size (FNS)
higher-order currents (HOC)

Four methods



Running treatment

$$\sum_{J_k, J, E_k^* \leqslant E_c}$$

- Closure
- Running Closure
- Running non-closure
- Mixed

Closure:

$$H_\alpha(r) = \frac{2R}{\pi}\int_0^\infty \frac{f_\alpha(q,r)qdq}{q+\boxed{\langle E\rangle},}$$

Non-closure:

$$H_\alpha(r, E_k) = \frac{2R}{\pi}\int_0^\infty \frac{f_\alpha(q,r)qdq}{q+\boxed{E_k-(E_i+E_f)/2}}$$

Running closure

$$\bar{M}_\alpha^{0\nu}(E_c) = M_\alpha^{0\nu}(E_c) - \mathcal{M}_\alpha^{0\nu}(E_c) + \mathcal{M}_\alpha^{0\nu}$$

Running non-closure

Closure

Y. Iwata, Nucl. Phys. Rev. (2017)

Calculation of neutrino pot part

$$H_\alpha(\sqrt{2}\rho) = \frac{2R}{\pi}\int_0^\infty f_\alpha(\sqrt{2}\rho q)\frac{h_{\alpha(q)}}{q+\langle E\rangle}\; q\; dq$$

Closure approx.

$$\sum_{n,n',l,l'} k_{n,n',l,l'} \langle \boxed{n'l'} \| H_\alpha(\sqrt{2}\rho) \| \boxed{nl} \rangle$$

Top 10 amplitude

	Fermi		Gamow-Teller		Tensor	
Ranking	$(n\ l\ n'\ l')$	Value	$(n\ l\ n'\ l')$	Value	$(n\ l\ n'\ l')$	Value
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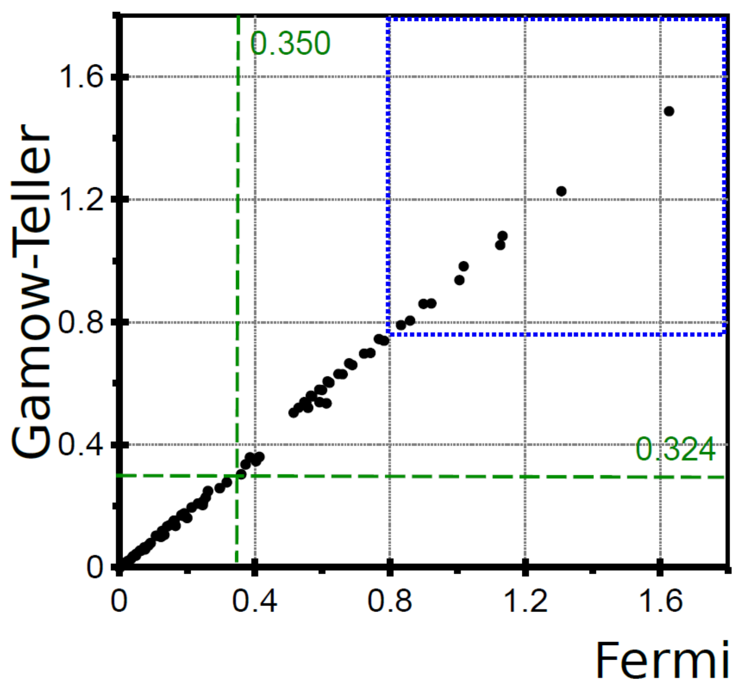

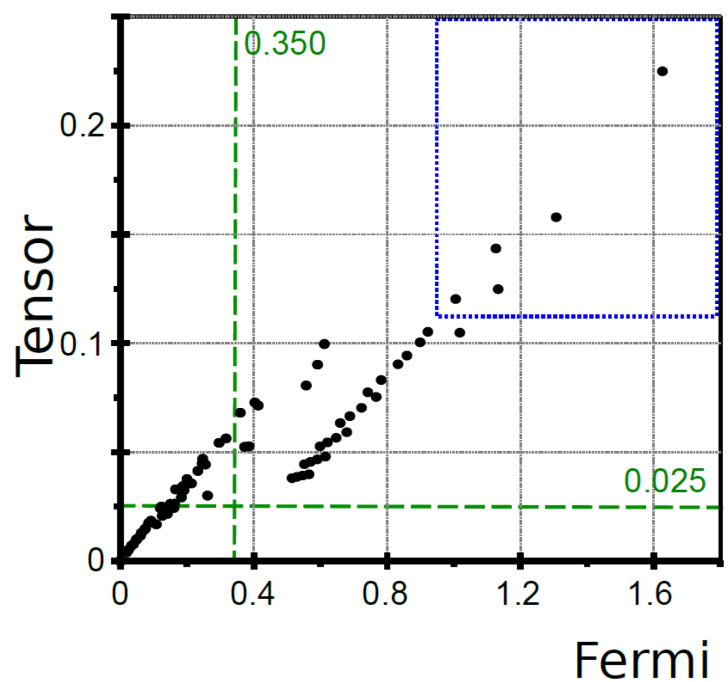

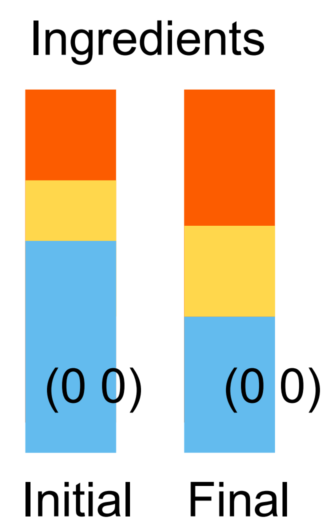

Shell model study of using an effective field theory for disentangling several contributions to neutrinoless double-β decay

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Weak interaction in nuclei represents a well-known venue for testing many of the fundamental symmetries of the Standard Model. In particular, neutrinoless double-β decay offers the possibility to test beyond Standard Model theories predicting that neutrinos are Majorana fermions and the lepton number conservation is violated. This paper focuses on an effective field theory approach to neutrinoless double-β decay for extracting information regarding the properties of the beyond Standard Model Lagrangian responsible for this process. We use shell model nuclear matrix elements and the latest experimental lower limits for the half-lives to extract 12 lepton-number-violating parameters of five nuclei of experimental interest and lower limits for the energy scales of the new physics. Using the most stringent limits that we obtain for the values of the lepton-number-violating parameters, we predict new half-life limits for the other nuclei of experimental interest, in the case of 12 neutrino double-β decay mechanisms. We provide an analysis that could reveal valuable information regarding the dominant neutrinoless double-β decay mechanism, if experimental half-life data become available for different isotopes.

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frontiers in Physics

The λ Mechanism of the $0\nu\beta\beta$-Decay

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The λ mechanism ($W_L - W_R$ exchange) of the neutrinoless double beta decay ($0\nu\beta\beta$-decay), which has origin in left-right symmetric model with right-handed gauge boson at TeV scale, is investigated. The revisited formalism of the $0\nu\beta\beta$-decay, which includes higher order terms of nucleon current, is exploited. The corresponding nuclear matrix elements are calculated within quasiparticle random phase approximation with partial restoration of the isospin symmetry for nuclei of experimental interest. A possibility to distinguish between the conventional light neutrino mass ($W_L - W_L$ exchange) and λ mechanisms by observation of the $0\nu\beta\beta$-decay in several nuclei is discussed. A qualitative comparison of effective lepton number violating couplings associated with these two mechanisms is performed. By making viable assumption about the seesaw type mixing of light and heavy neutrinos with the value of Dirac mass m_D within the range $1\ \mathrm{MeV} < m_D < 1\ \mathrm{GeV}$, it is concluded that there is a dominance of the conventional light neutrino mass mechanism in the decay rate.

Keywords: majorana neutrinos, neutrinoless double beta decay, right-handed current, left-right symmetric models, nuclear matrix elements, quasiparticle random phase approximation

$$^{48}\mathrm{Ca} \rightarrow {}^{48}\,\mathrm{Ti} + e^{-} + e^{-}$$

Matrix elements [L-L type]

SRC = Short range correlation (短距離相関)

TABLE I. Nuclear matrix elements M_F, M_GT, M_T, M_ν for $0\nu\beta\beta$ of ^{48}Ca, calculated with GXPF1A interaction in closure, running closure, running nonclosure and mixed methods for different SRC parametrization. $\langle E\rangle$ = 7.72 MeV was used for closure and running closure methods.

NME	SRC	Closure	Running closure	Running nonclosure	Mixed
M_F	None	-0.207	-0.206	-0.210	-0.211
M_F	Miller-Spencer	-0.141	-0.141	-0.143	-0.143
M_F	CD-Bonn	-0.222	-0.221	-0.226	-0.227
M_F	AV18	-0.204	-0.203	-0.207	-0.208
M_{GT}	None	0.711	0.709	0.779	0.781
M_{GT}	Miller-Spencer	0.492	0.490	0.553	0.555
M_{GT}	CD-Bonn	0.738	0.736	0.810	0.812
M_{GT}	AV18	0.675	0.673	0.745	0.747
M_T	None	-0.074	-0.072	-0.074	-0.076
M_T	Miller-Spencer	-0.076	-0.073	-0.075	-0.078
M_T	CD-Bonn	-0.076	-0.074	-0.076	-0.078
M_T	AV18	-0.077	-0.074	-0.076	-0.079
M_ν	None	0.765	0.765	0.836	0.836
M_ν	Miller-Spencer	0.504	0.505	0.566	0.565
M_ν	CD-Bonn	0.799	0.799	0.874	0.874
M_ν	AV18	0.725	0.725	0.798	0.798

Total

Matrix elements [q type]

TABLE III. Nuclear matrix elements M_{qF}, M_{qGT}, M_{qT}, M_{1+}, and M_{2-} for $0\nu\beta\beta$ of ^{48}Ca calculated with GXPF1A interaction in closure, running closure, running nonclosure and mixed methods for different SRC parametrization. $\langle E \rangle = 7.72$ MeV was used for closure and running closure methods.

NME	SRC	Closure	Running closure	Running nonclosure	Mixed
M_{qF}	None	-0.102	-0.102	-0.101	-0.101
M_{qF}	Miller-Spencer	-0.082	-0.082	-0.080	-0.080
M_{qF}	CD-Bonn	-0.123	-0.122	-0.121	-0.122
M_{qF}	AV18	-0.118	-0.118	-0.117	-0.117
M_{qGT}	None	3.243	3.246	3.317	3.314
M_{qGT}	Miller-Spencer	2.681	2.684	2.751	2.748
M_{qGT}	CD-Bonn	3.554	3.557	3.709	3.706
M_{qGT}	AV18	3.423	3.426	3.502	3.499
M_{qT}	None	-0.147	-0.140	-0.143	-0.150
M_{qT}	Miller-Spencer	-0.150	-0.143	-0.146	-0.153
M_{qT}	CD-Bonn	-0.149	-0.142	-0.145	-0.153
M_{qT}	AV18	-0.150	-0.142	-0.146	-0.153
M_{1+}	None	3.937	3.898	3.989	4.028
M_{1+}	Miller-Spencer	3.430	3.389	3.480	3.521
M_{1+}	CD-Bonn	4.221	4.183	4.356	4.394
M_{1+}	AV18	4.101	4.061	4.158	4.198
M_{2-}	None	0.275	0.279	0.378	0.374
M_{2-}	Miller-Spencer	0.085	0.090	0.172	0.167
M_{2-}	CD-Bonn	0.271	0.276	0.372	0.367
M_{2-}	AV18	0.214	0.220	0.319	0.313

Total

The amplitude of matrix element for L-R exchange
are relatively large compared to the cases with L-L exchange.

Closure-energy dependence

[constant] no significant change is noticed in several settings

In closure approximation

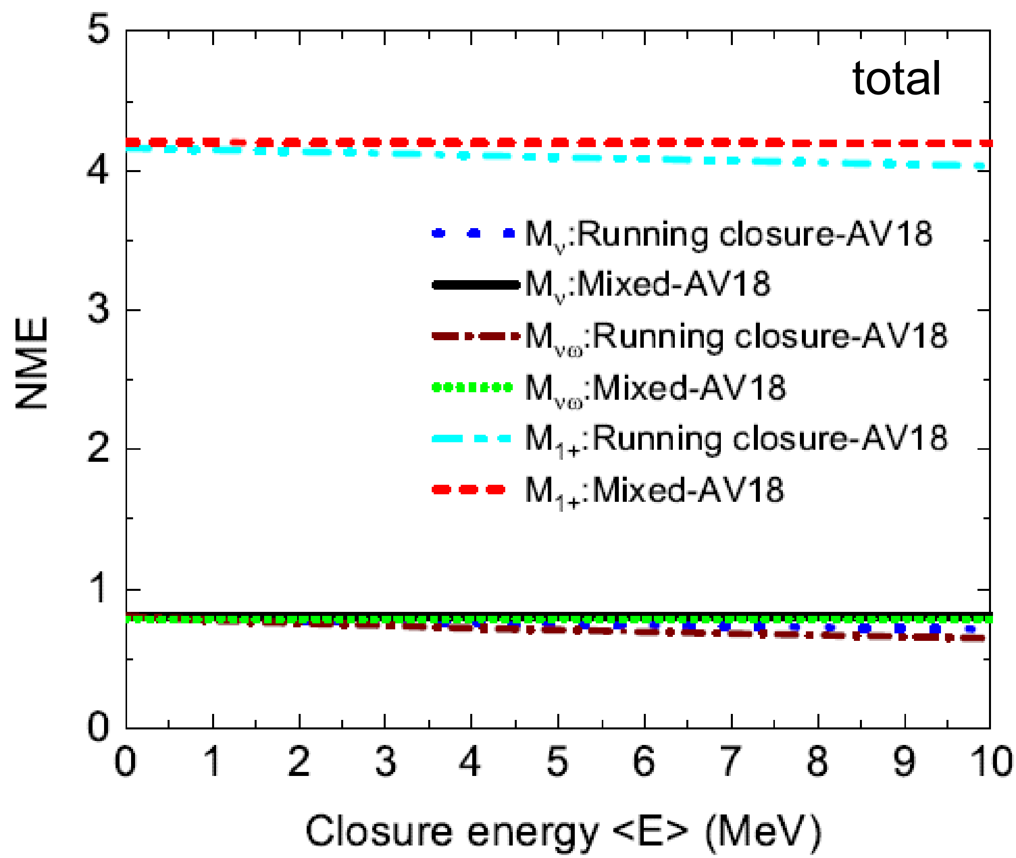


FIG. 6. (Color online) Dependence of the total NMEs for $0\nu\beta\beta$ (λ and $m_{\beta\beta}$ mechanisms) of ^{48}Ca with closure energy $\langle E\rangle$, calculated with total GXPF1A interaction for AV18 SRC parmaetrization in running closure and mixed methods.

NME values

$$[T^{0\nu}_{1/2}]^{-1} = \boxed{\eta_\nu^2 C_{mm}} + \boxed{\eta_\lambda^2 C_{\lambda\lambda}} + \eta_\nu \eta_\lambda \cos\psi C_{m\lambda}$$

NME	SRC	Closure	Running closure	Running nonclosure		Mixed
M_ν	None	0.765	0.765	0.836		0.836
M_ν	Miller-Spencer	0.504	0.505	0.566	x 1	0.565
M_ν	CD-Bonn	0.799	0.799	0.874		0.874
M_ν	AV18	0.725	0.725	0.798		0.798
M_{1+}	None	3.937	3.898	3.989		4.028
M_{1+}	Miller-Spencer	3.430	3.389	3.480	x 5	3.521
M_{1+}	CD-Bonn	4.221	4.183	4.356		4.394
M_{1+}	AV18	4.101	4.061	4.158		4.198
M_{2-}	None	0.275	0.279	0.378		0.374
M_{2-}	Miller-Spencer	0.085	0.090	0.172		0.167
M_{2-}	CD-Bonn	0.271	0.276	0.372	x 1/2	0.367
M_{2-}	AV18	0.214	0.220	0.319		0.313

$$C_{mm} = g_A^4 \boxed{M_\nu^2 G_{01}},$$

*1 (std)

$$C_{m\lambda} = -g_A^4 M_\nu (M_{2-} G_{03} - M_{1+} G_{04})$$

$$C_{\lambda\lambda} = g_A^4 (\underbrace{M_{2-}^2 G_{02}}_{\text{large}\sim *10} + \frac{1}{9}\underbrace{M_{1+}^2 G_{011}}_{\text{small}\sim 1/10} - \frac{2}{9}\underbrace{M_{1+}M_{2-}G_{010}}_{\sim *1})$$

Effect should not be negligible.

$C_{\lambda\lambda}$ 1st : enlarged amplitude (*5)

$C_{\lambda\lambda}$ 2nd : comparable amplitude (*1/2)

$C_{\lambda\lambda}$ 3rd : enlarged amplitude (*2.5)

Results

we have found
the large WR-WL effect

almost 2 times larger than WL-WL

$$g_V(q^2) = \frac{g_V}{\left(1+\frac{q^2}{M_V^2}\right)^2},$$

$$g_A(q^2) = \frac{g_A}{\left(1+\frac{q^2}{M_A^2}\right)^2},$$

$$g_M(q^2) = (\mu_p - \mu_n) g_V(q^2),$$

$$g_P(q^2) = \frac{2m_p g_A(q^2)}{(q^2+m_\pi^2)}\left(1-\frac{m_\pi^2}{M_A^2}\right)$$

$$f_{GT}(q,r) = \frac{j_0(qr)}{g_A^2}\left(g_A^2(q^2) - \frac{g_A(q^2)g_P(q^2)}{m_N}\frac{q^2}{3} + \frac{g_P^2(q^2)}{4m_N^2}\frac{q^4}{3} + \left(2\frac{g_M^2(q^2)}{4m_N^2}\frac{q^2}{3}\right)\right), \tag{15}$$

$$f_F(q,r) = g_V^2(q^2) j_0(qr), \tag{16}$$

$$f_T(q,r) = \frac{j_2(qr)}{g_A^2}\left(\frac{g_A(q^2)g_P(q^2)}{m_N}\frac{q^2}{3} - \frac{g_P^2(q^2)}{4m_N^2}\frac{q^4}{3} + \frac{g_M^2(q^2)}{4m_N^2}\frac{q^2}{3}\right), \tag{17}$$

$$f_{\omega GT}(q,r) = \frac{q}{(q+E_k-(E_i+E_f)/2)} f_{GT}(q,r), \tag{18}$$

$$f_{\omega F}(q,r) = \frac{q}{(q+E_k-(E_i+E_f)/2)} f_F(q,r), \tag{19}$$

$$f_{\omega T}(q,r) = \frac{q}{(q+E_k-(E_i+E_f)/2)} f_T(q,r), \tag{20}$$

$$f_{qGT}(q,r) = \left(\frac{g_A^2(q^2)}{g_A^2}q \boxed{+ 3\frac{g_P^2(q^2)}{g_A^2}\frac{q^5}{4m_N^2}} \boxed{+ \frac{g_A(q^2)g_P(q^2)}{g_A^2}\frac{q^3}{m_N}}\right) r j_1(q,r), \tag{21}$$

$$f_{qF}(q,r) = r g_V^2(q^2) j_1(qr) q, \tag{22}$$

$$f_{qT}(q,r) = \frac{r}{3}\left(\left(\frac{g_A^2(q^2)}{g_A^2}q - \frac{g_P(q^2)g_A(q^2)}{2g_A^2}\frac{q^3}{m_N}\right) j_1(qr) - \left(9\frac{g_P^2(q^2)}{2g_A^2}\frac{q^5}{20m_N^2}\left[2j_1(qr)/3 - j_3(qr)\right]\right)\right),$$

Previous shell model calculation did not calculate/find the importance of 2nd and 3rd terms

Not calculated in
Horoi, Neascu, PRC 2018

Heavy neutrino (right-handed neutrino)

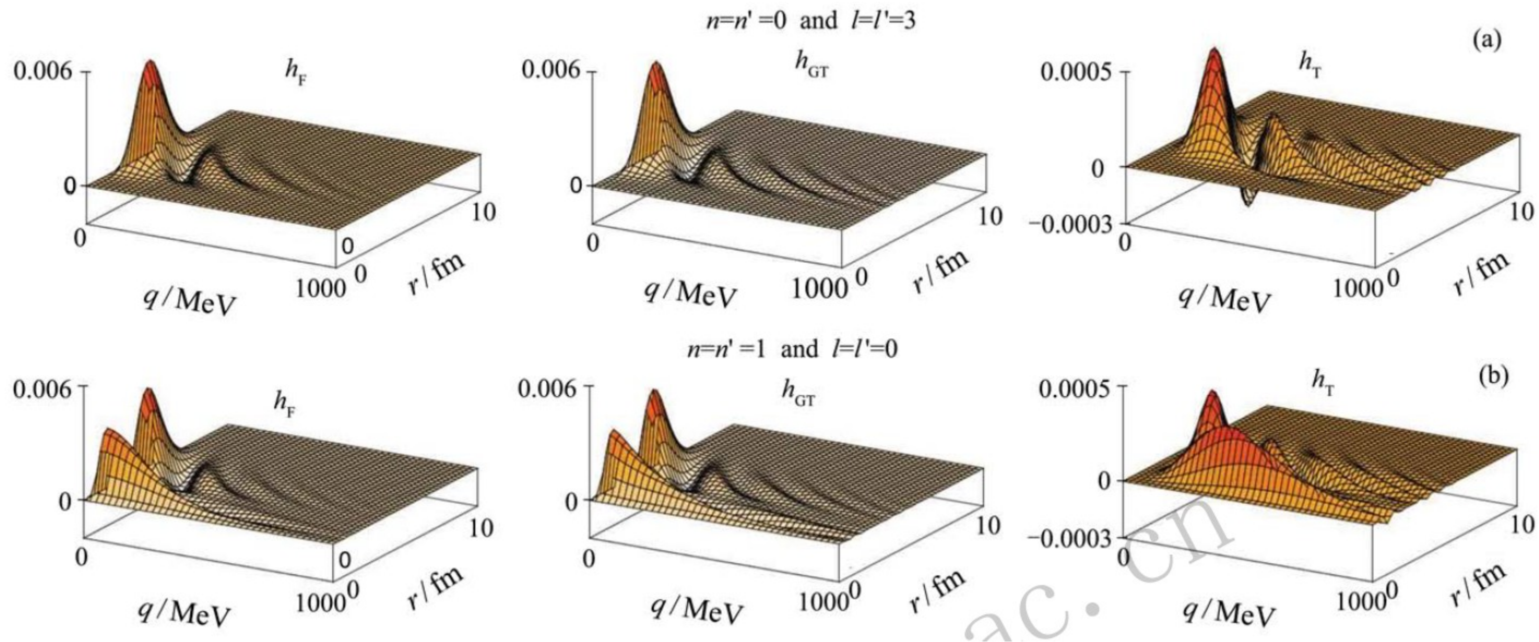
$$[T^{1/2}_{0\nu}]^{-1} = \boxed{G\left\{|M^{0\nu}|^2\left(\frac{m_\nu}{m_e}\right)^2}+|M^{0N}|^2(\eta_N)^2\right\}$$

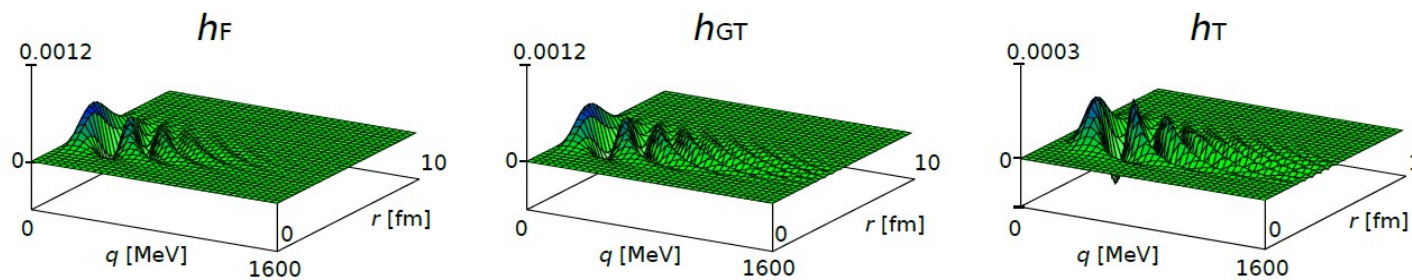
J. D. Vergados, H. Ejiri, and F. Simkovic, Rep. Prog. Phys. 75, 106301 (2012)
M. Horoi, Phys. Rev. C 87, 014320 (2013)

To be compared to …

$$\boxed{[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q,Z)g_A^4|M^{0\nu}|^2\frac{|m_{\beta\beta}|^2}{m_e^2}}$$

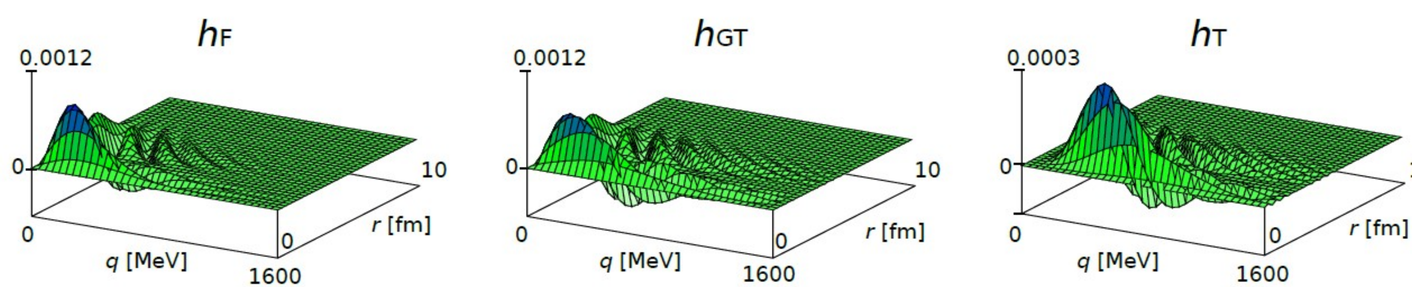
Light neutrino





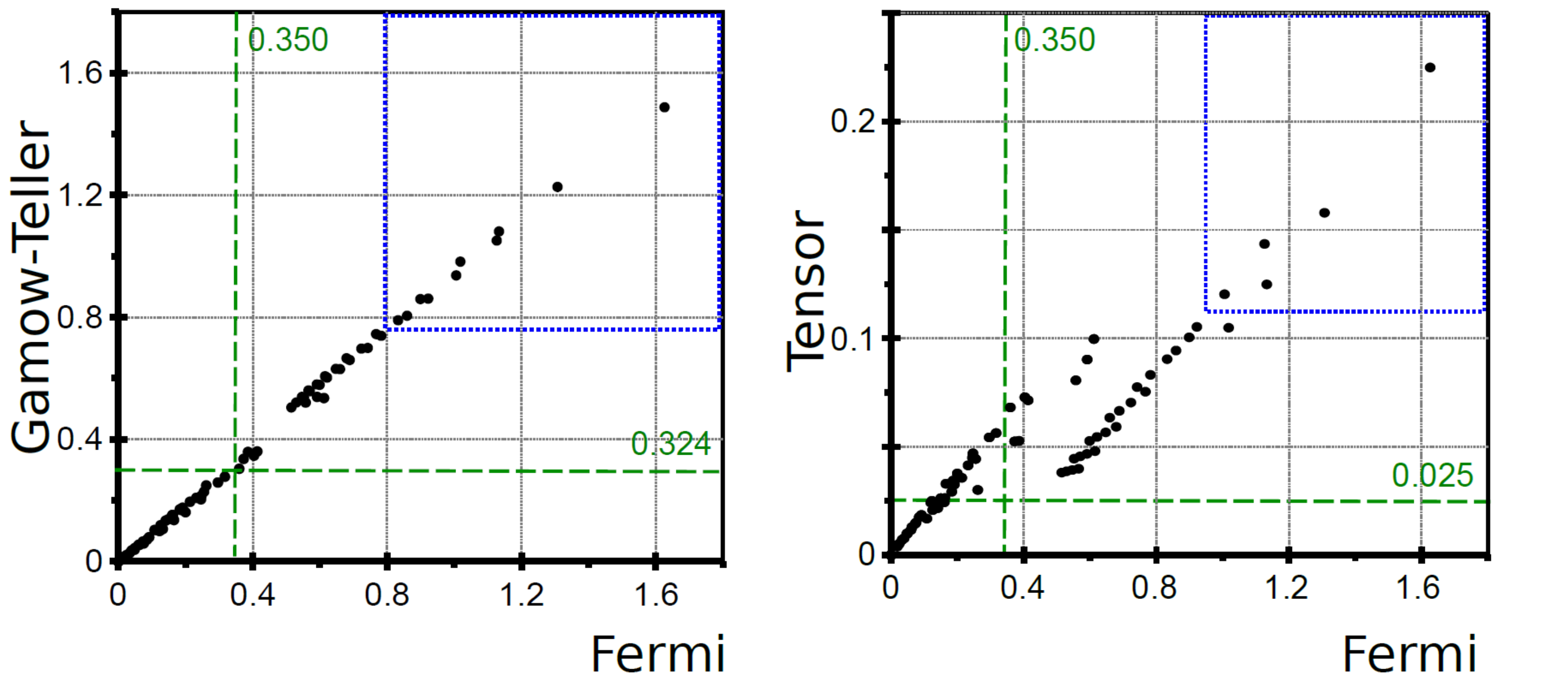
(a) $n = n' = 0$ and $l = l' = 3$

Heavy neutrino

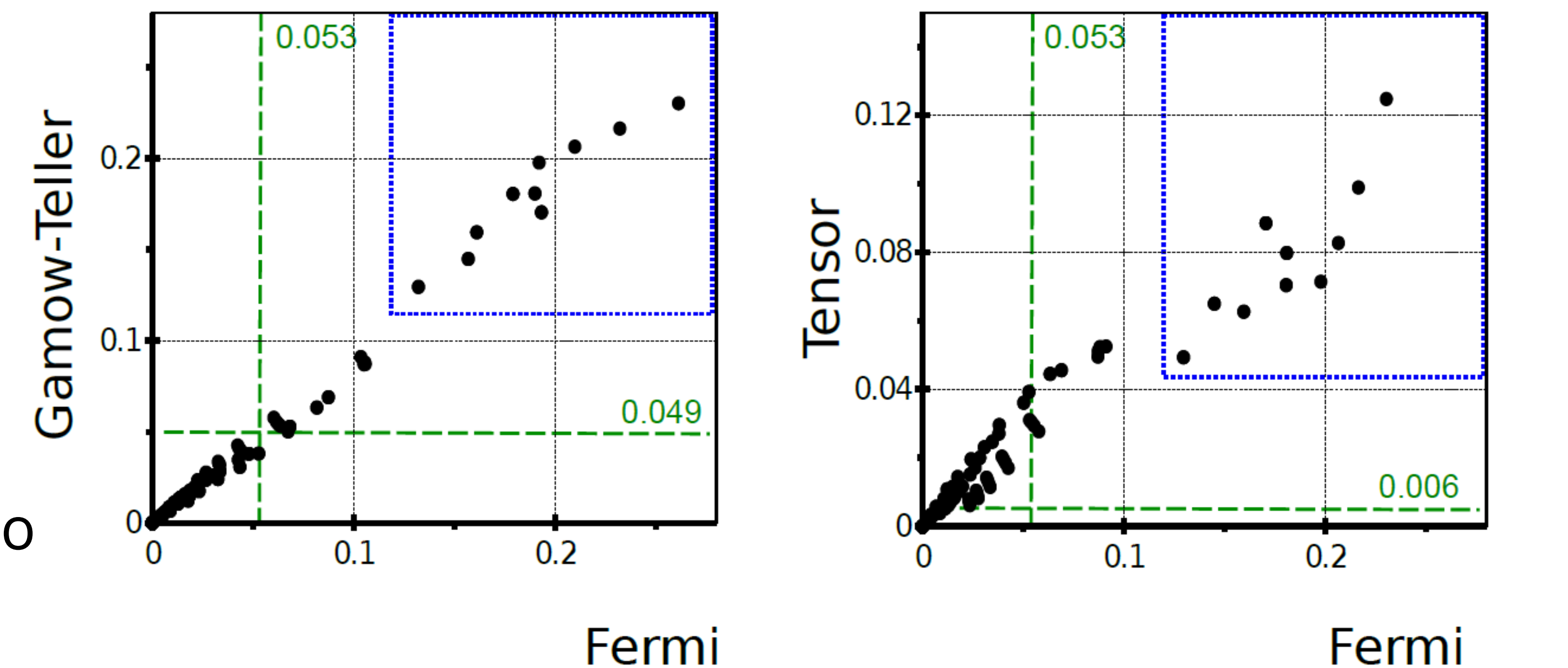


(b) $n = n' = 1$ and $l = l' = 0$

Light neutrino

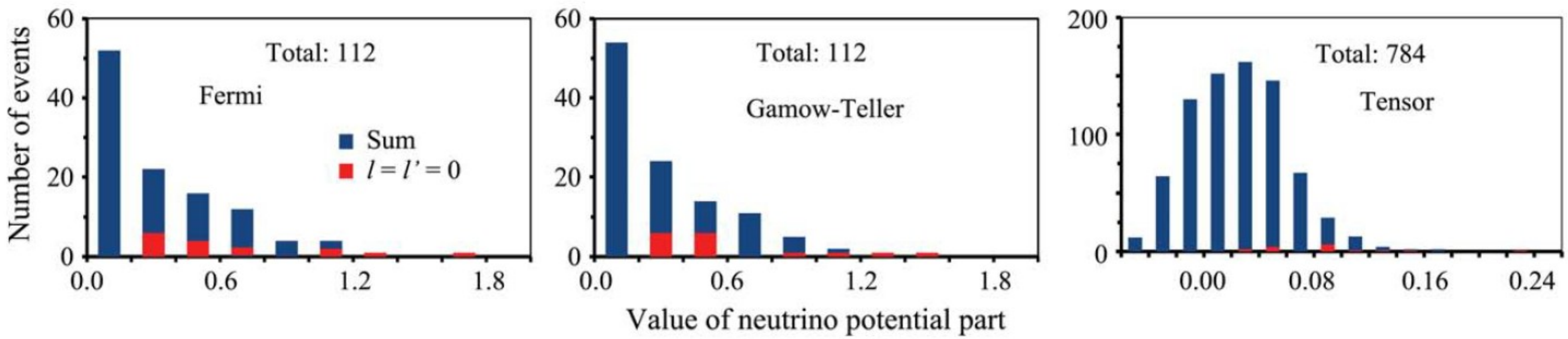


Heavy neutrino



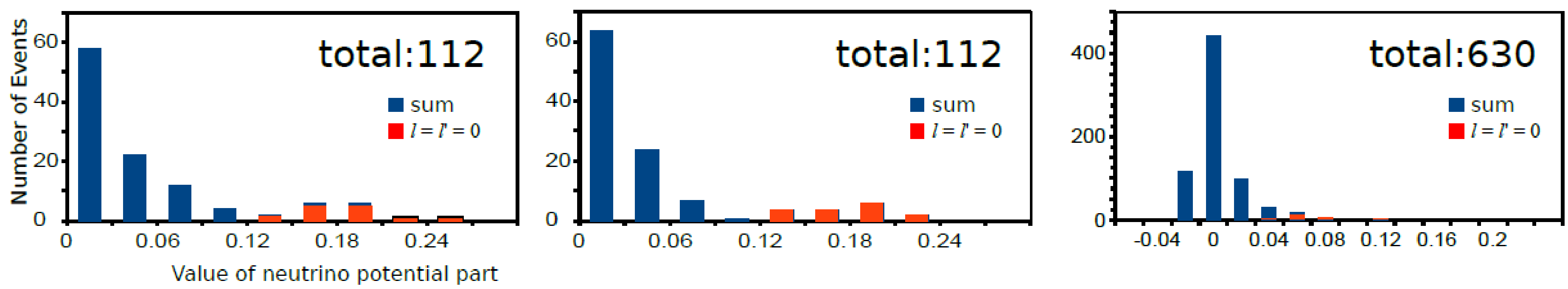
Light neutrino

Fermi **Gamow-Teller** **Tensor**



Heavy neutrino

Fermi Gamow-Teller Tensor



Sterile neutrino search based on Verdados, Ejiri, et al. Prog. Phys. C 2012

$$[T^{1/2}_{0\nu,\mathrm{I}}]^{-1} = G_I \left\{ |M^{0\nu}_{\mathrm{I}}|^2 \left(\frac{m_\nu}{m_e}\right)^2 + |M^{0N}_{\mathrm{I}}|^2 (\eta_N)^2 \right\}$$

$$[T^{1/2}_{0\nu,\mathrm{II}}]^{-1} = G_{II} \left\{ |M^{0\nu}_{\mathrm{II}}|^2 \left(\frac{m_\nu}{m_e}\right)^2 + |M^{0N}_{\mathrm{II}}|^2 (\eta_N)^2 \right\}$$

assumption

$$|M^{0N}_{\mathrm{I}}|^2/|M^{0\nu}_{\mathrm{I}}|^2 \neq |M^{0N}_{\mathrm{II}}|^2/|M^{0\nu}_{\mathrm{II}}|^2$$

$$\left(\frac{m_\nu}{m_e}\right)^2 = \frac{[G_I T^{1/2}_{0\nu,\mathrm{I}}]^{-1}}{|M^{0\nu}_{\mathrm{I}}|^2} \frac{|M^{0\nu}_{\mathrm{II}}|^2|M^{0N}_{\mathrm{I}}|^2 - |M^{0\nu}_{\mathrm{I}}|^2|M^{0N}_{\mathrm{II}}|^2}{|M^{0\nu}_{\mathrm{II}}|^2|M^{0N}_{\mathrm{I}}|^2 - |M^{0\nu}_{\mathrm{I}}|^2|M^{0N}_{\mathrm{II}}|^2} = \frac{1}{G_I} \frac{[T^{1/2}_{0\nu,\mathrm{I}}]^{-1}}{|M^{0\nu}_{\mathrm{I}}|^2}$$

$$(\eta_N)^2 = \frac{|M^{0\nu}_{\mathrm{II}}|^2[G_I T^{1/2}_{0\nu,\mathrm{I}}]^{-1} - |M^{0\nu}_{\mathrm{I}}|^2[G_{II} T^{1/2}_{0\nu,\mathrm{II}}]^{-1}}{|M^{0\nu}_{\mathrm{II}}|^2|M^{0N}_{\mathrm{I}}|^2 - |M^{0\nu}_{\mathrm{I}}|^2|M^{0N}_{\mathrm{II}}|^2},$$

Summary

- Effect of right handed weak bosons ?

- Effect of right handed neutrino --- sterile neutrinos ?

Towards …

$$
\begin{aligned}
[T^{0\nu}_{1/2}]^{-1} &= \frac{\Gamma^{0\nu}}{\ln 2} \\
&= g_A^4 |M_{GT}|^2 \left\{ C_{mm} \left(\frac{|m_{\beta\beta}|}{m_e} \right)^2 + C_{m\lambda} \frac{|m_{\beta\beta}|}{m_e} \langle \lambda \rangle \cos \psi_1 \right. \\
&\quad + C_{m\eta} \frac{|m_{\beta\beta}|}{m_e} \langle \eta \rangle \cos \psi_2 + C_{\lambda\lambda} \langle \lambda \rangle^2 + C_{\eta\eta} \langle \eta \rangle^2 \\
&\quad \left. + C_{\lambda\eta} \langle \lambda \rangle \langle \eta \rangle \cos (\psi_1 - \psi_2) \right\}.
\end{aligned}
$$

Terasaki, Iwata, submitted

arXiv:2104.08250

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Nuclear Theory

[Submitted on 16 Apr 2021 (v1), last revised 14 May 2021 (this version, v2)]

Estimation of nuclear matrix elements of double-β decay from shell model and quasiparticle random-phase approximation

J. Terasaki, Y. Iwata

The nuclear matrix element (NME) of the neutrinoless double-β ($0\nu\beta\beta$) decay is an essential input for determining the neutrino effective mass, if the half-life of this decay is measured. The reliable calculation of this NME has been a long-standing problem because of the diversity of the predicted values of the NME depending on the calculation method. In this paper, we focus on the shell model and the QRPA. The shell model have a rich amount of the many-particle many-hole correlations, and the QRPA can obtain the convergence of the result of calculation with respect to the extension of the single-particle space. It is difficult for the shell model to obtain the convergence of the $0\nu\beta\beta$ NME with respect to the valence single-particle space. The many-body correlations of the QRPA are insufficient depending on nuclei. We propose a new method to modify phenomenologically the results of the shell model and the QRPA compensating the insufficient point of each method by using the information of other method complementarily. Extrapolations of the components of the $0\nu\beta\beta$ NME of the shell model are made toward a very large valence single-particle space. We introduce a modification factor to the components of the $0\nu\beta\beta$ NME of the QRPA. Our modification method gives similar values of the $0\nu\beta\beta$ NME of the two methods for ^{48}Ca. The NME of the two-neutrino double-β decay is also modified in a similar but simpler manner, and the consistency of the two methods is improved.

Comments: 21 pages, 4 figures, section VII was modified
Subjects: **Nuclear Theory (nucl-th)**; Nuclear Experiment (nucl-ex)
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(or arXiv:2104.08250v2 **[nucl-th]** for this version)

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