Neutrinoless double beta decaymatrix element without closure approximation

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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

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

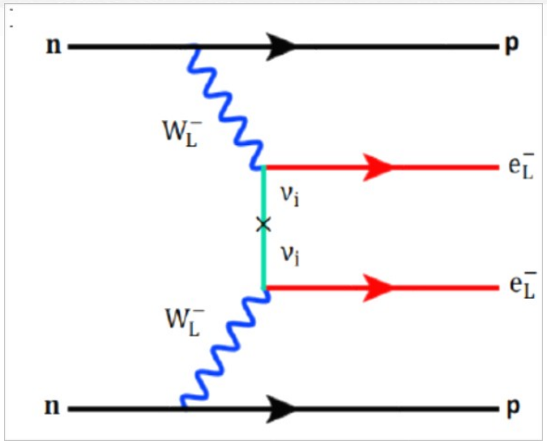
m_e :electron mass

Effective Majorana neutrino mass

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

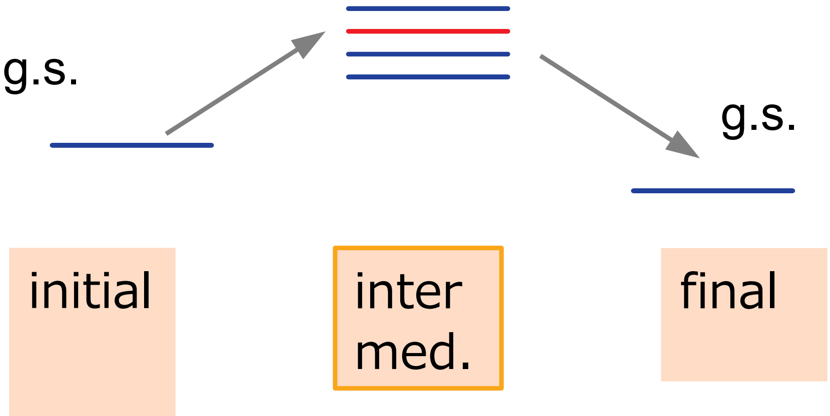
Uei : Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix

Theoretical interests from only technical point of view



1. **Full version** of matrix element
   → left-right asymmetry, tensor part

2. Closure and **non-closure** matrix element



1. Full version of matrix element

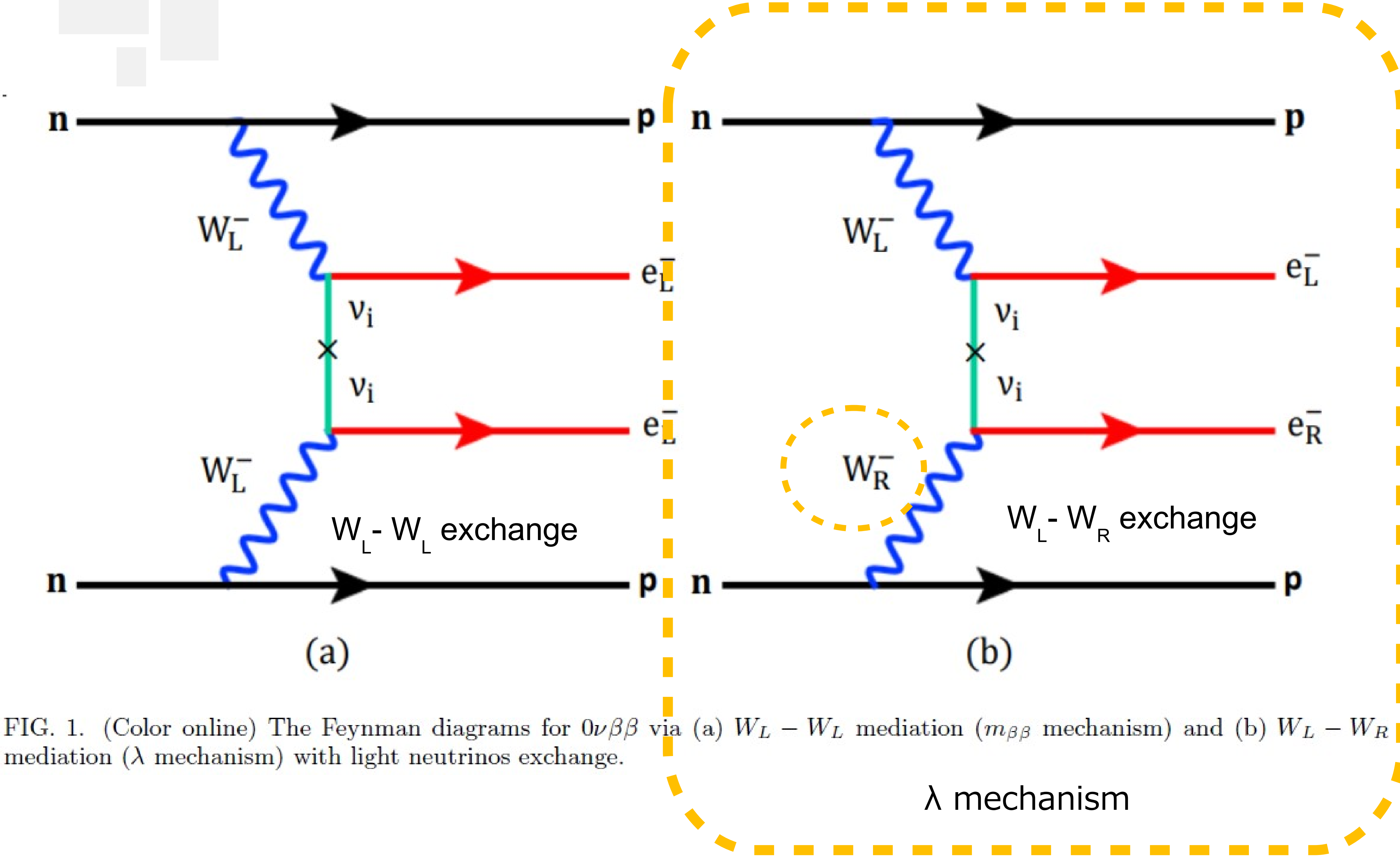
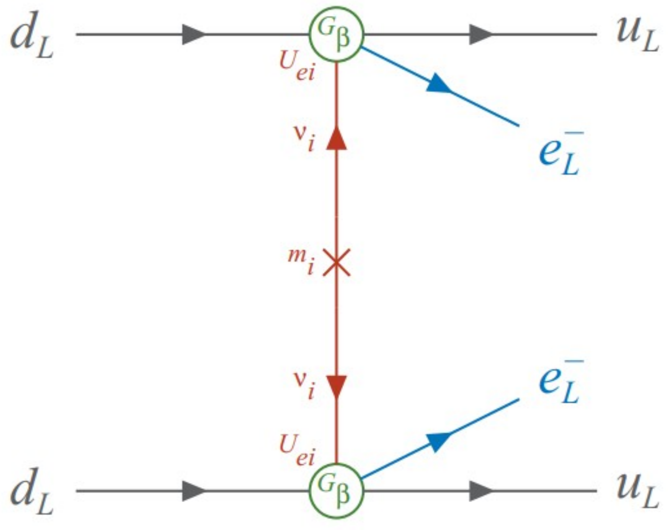
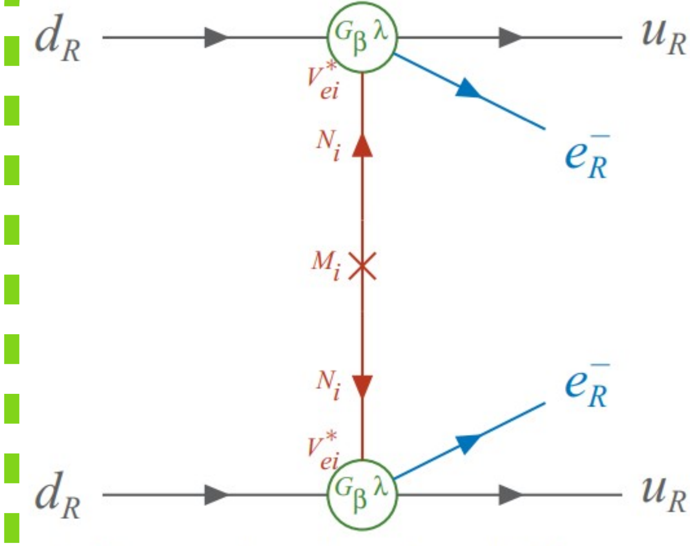


FIG. 1. (Color online) The Feynman diagrams for $0\nu\beta\beta$ via (a) $W_L - W_L$ mediation ($m_{\beta\beta}$ mechanism) and (b) $W_L - W_R$ mediation (λ mechanism) with light neutrinos exchange.

Ordinary case

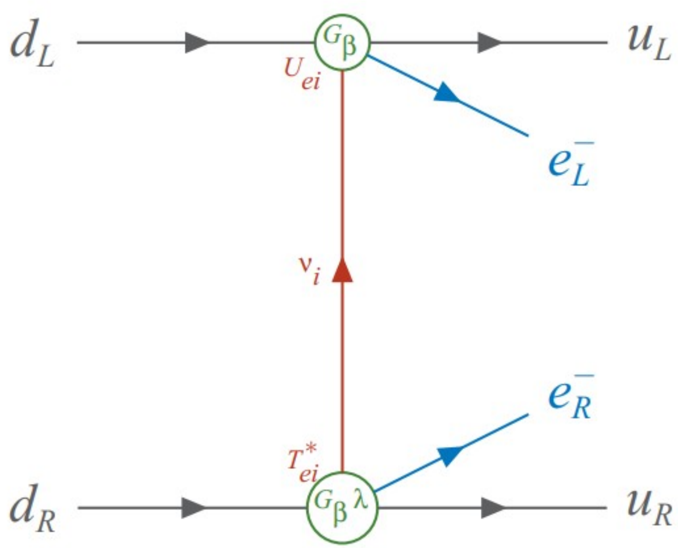


(a) Light neutrino exchange for purely LH currents. Diagram $\propto \eta_m$ arising from $j_L J_L^\dagger j_L J_L^\dagger$ term.

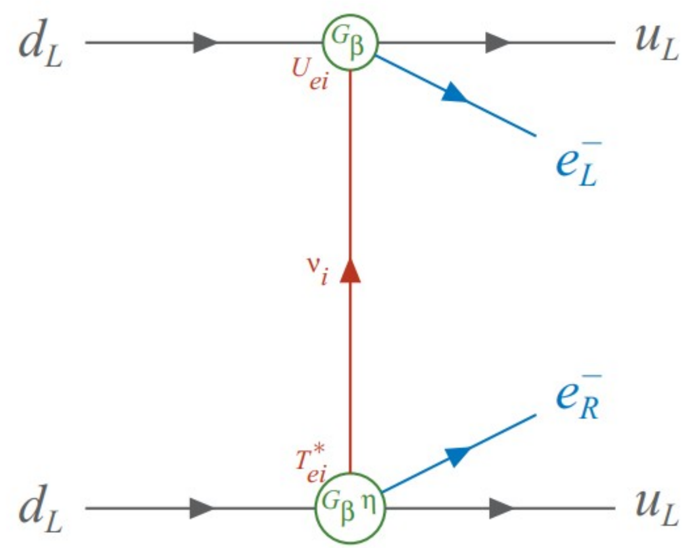


(b) Heavy neutrino exchange for purely RH currents. Diagram $\propto \eta_N$ arising from $j_R J_R^\dagger j_R J_R^\dagger$ term.

FIG. 2. Relevant diagrams for $0\nu\beta\beta$ in LRSM for both electrons of same chirality.



(a) λ-diagram due to both LH and RH currents. Diagram $\propto \eta_\lambda$ arising from $j_L J_L^\dagger j_R J_R^\dagger$ term.



(b) η-diagram due to gauge boson mixing. Diagram $\propto \eta_\eta$ arising from $j_L J_L^\dagger j_R J_L^\dagger$ term.

FIG. 3. Relevant diagrams for $0\nu\beta\beta$ in LRSM for both electrons of opposite chirality.

A question in front of us:

Is **the natural law** asymmetric？

or

Does **the asymmetry** underlie in the property of elementary particle？

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

PHYSICAL REVIEW C **102**, 034317 (2020)

Nuclear matrix elements for the λ mechanism of $0\nu\beta\beta$ decay of ^{48}Ca in the nuclear shell-model: Closure versus nonclosure approach

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The λ and $m_{\beta\beta}$ mechanisms of neutrinoless double beta decay ($0\nu\beta\beta$) occur with light neutrino exchange via $W_L - W_R$ and $W_L - W_L$ mediation, respectively. In the present study, we calculate the nuclear matrix elements (NMEs) for the $m_{\beta\beta}$ and λ mechanisms of $0\nu\beta\beta$, which has origin in the left-right symmetric model with right-handed gauge boson at TeV scale. The NMEs are calculated for one of the $0\nu\beta\beta$ decaying isotope ^{48}Ca in the interacting nuclear shell-model using the GXPF1A effective interaction of pf shell. The NMEs are calculated in both closure and nonclosure approaches using four different methods: closure, running closure, running nonclosure, and mixed methods. All the NMEs are calculated incorporating the effects of the finite size of nucleons and the revisited higher-order terms such as pseudoscalar and weak magnetism terms of the nucleon currents. Inclusion of the short-range nature of nucleon-nucleon interaction in Miller-Spencer, CD-Bonn, and AV18 parametrizations is also taken care of. We have used closure energy $\langle E \rangle = 0.5$ MeV, which is near to the optimal value of closure energy that is extracted by examining the dependence of NMEs with closure energy in closure and mixed methods. The comparative dependence of the running closure and running nonclosure NMEs with the spin-parity of the allowed states of intermediate nucleus ^{48}Sc, the coupled spin-parity of the two initial decaying neutrons and the final two protons, the cutoff excitation energy of ^{48}Sc, and the cutoff number of states of ^{48}Sc are examined. The neutrino momentum and radial distribution of different types of NMEs are explored. It is found that there is a significant enhancement in M_{qGT}-type NMEs, which originates from the large momentum distribution for the inclusion of the higher-order pseudoscalar term of the nucleon currents.

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Interacting shell model calculations for neutrinoless double beta decay of ^{82}Se with left-right weak boson exchange

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Table 3. Results for half-life and bounds on neutrino mass and lepton number violating parameters. The $T_{1/2}^{0\nu-exp}$ is taken from the experimental lower limit on half-life from Ref. [43] for ^{82}Se and from Ref. [44] for ^{48}Ca. All results are for AV18 type SRC parameterizaion. We have assumed CP conservation ($\psi = 0$)

Quantity	^{82}Se	^{48}Ca
$T_{1/2}^{0\nu-exp}$ [Years]	2.5×10^{23}	2.0×10^{22}
C_{mm} [Years]$^{-1}$	31.21×10^{-14}	4.06×10^{-14}
$C_{m\lambda}$ [Years]$^{-1}$	10.46×10^{-14}	3.37×10^{-14}
$C_{\lambda\lambda}$ [Years]$^{-1}$	36.19×10^{-14}	5.39×10^{-14}
$m_{\beta\beta}$ [eV]	1.83	17.92
η_λ	3.32×10^{-6}	30.44×10^{-6}

PHYSICAL REVIEW C **101**, 035504 (2020)

Interference effects for $0\nu\beta\beta$ decay in the left-right symmetric model

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Various mechanisms may contribute to neutrinoless double beta decay in the left-right symmetric model. The interference between these mechanisms also contribute to the overall decay rate. The analysis of the contributions of these interference terms is important for disentangling different mechanisms. In the present paper we study interference effects contributing to the decay rate for neutrinoless double-β decay in the left-right symmetric model. The numerical values for maximum interference for several nuclides are calculated. It is observed that, for most of the interference terms, the contribution is smaller than 20% for all the nuclei considered in the study. However, the interference between the mass mechanisms (light and heavy) and η mechanism is observed to be in the range 30%–50%. The variation of the interference effect with the Q values is also studied.

DOI: 10.1103/PhysRevC.101.035504

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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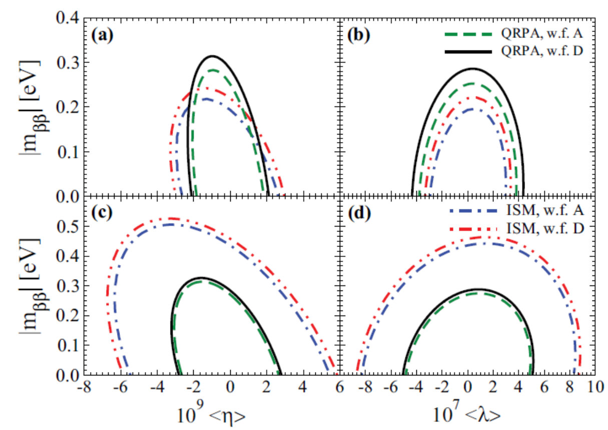
Left-right symmetric model

- *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

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

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

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

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

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

diagonalize

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.

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

$m_{\rm LNV}$ is the total lepton number violating scale

Hadronic current (with nonrelativistic assump.)

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

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

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

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

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

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

$$\chi = \eta$$

$$G_\beta = G_F \cos\theta_C$$

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**

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

Only GT is shown here

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

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

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

To be compared to ...

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

Neutrinoless DBD Matrix element

in left-right symmetric model

[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}	

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

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

usual WL-WL exchange

New

Matrix element

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

small~1/10 small~1/10

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

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

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

Effective lepton number violation parameters

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

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

Pontecorvo-Maki-Nakagawa-Sakata matrix

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

$$g_A = 1.27$$

bare

[Simkovic 2017] For Ca,

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

Detail of calculations

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

F, GT, T

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

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

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

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

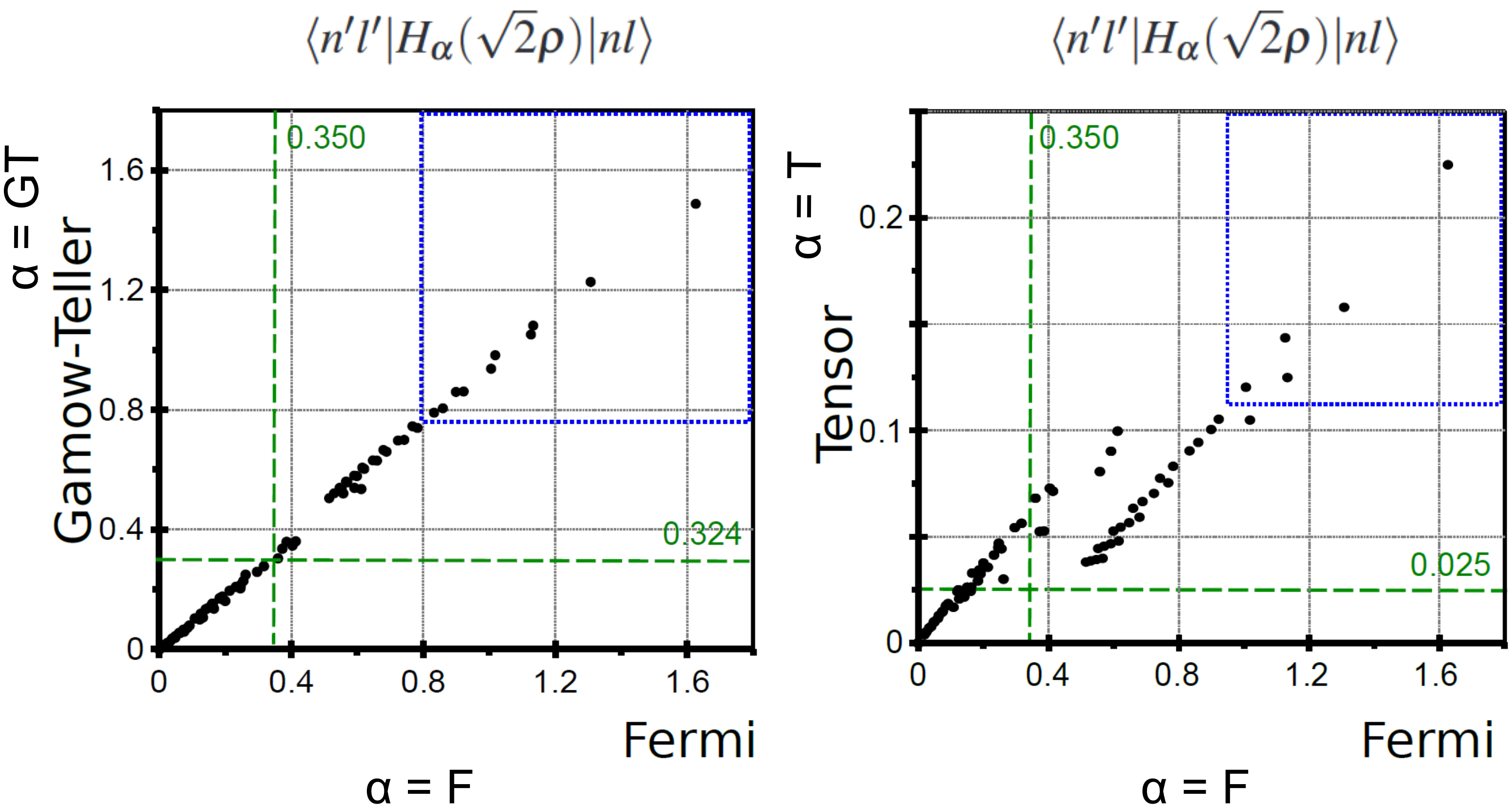
Included:
finite nucleon size (FNS)
higher-order currents (HOC)

Tensor part ?

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

α = F, GT, T (Fermi, Gamow-Teller, and tensor parts)

Standard mechanism



All the cases are examined for ...

n, n′ = 0, 1, · · · , 3

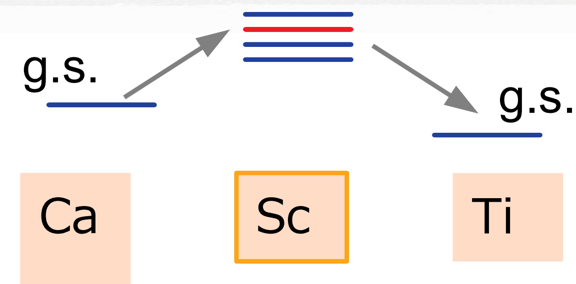
l, l′ = 0, 1, · · · , 6

2.Non-closure approx.

Four methods

Running treatment

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



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

Closure:

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

Non-closure:

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

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

Closure approximation ?

^{48}Ca

Two neutrino process

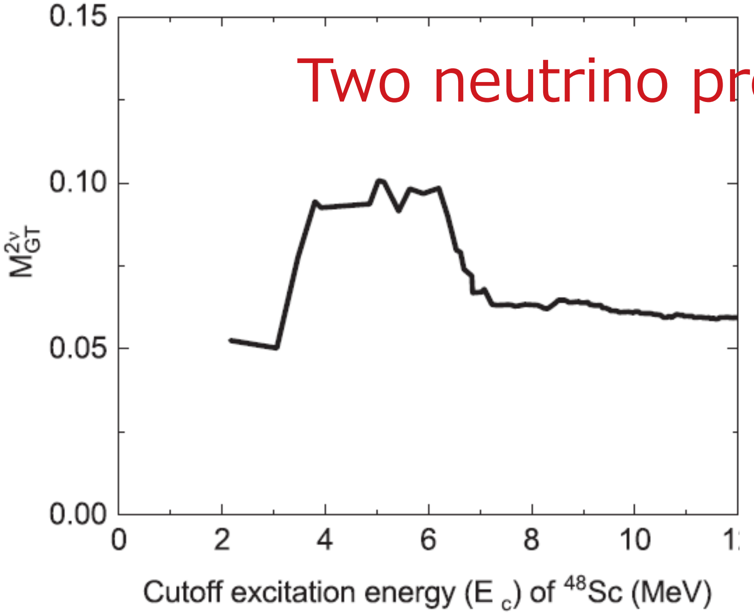


FIG. 10. Variation of NME for $2\nu\beta\beta$ of ^{48}Ca with cutoff excita-
tion energy (E_c) of 1^+ states of the virtual intermediate nucleus ^{48}S

Neutrinoless

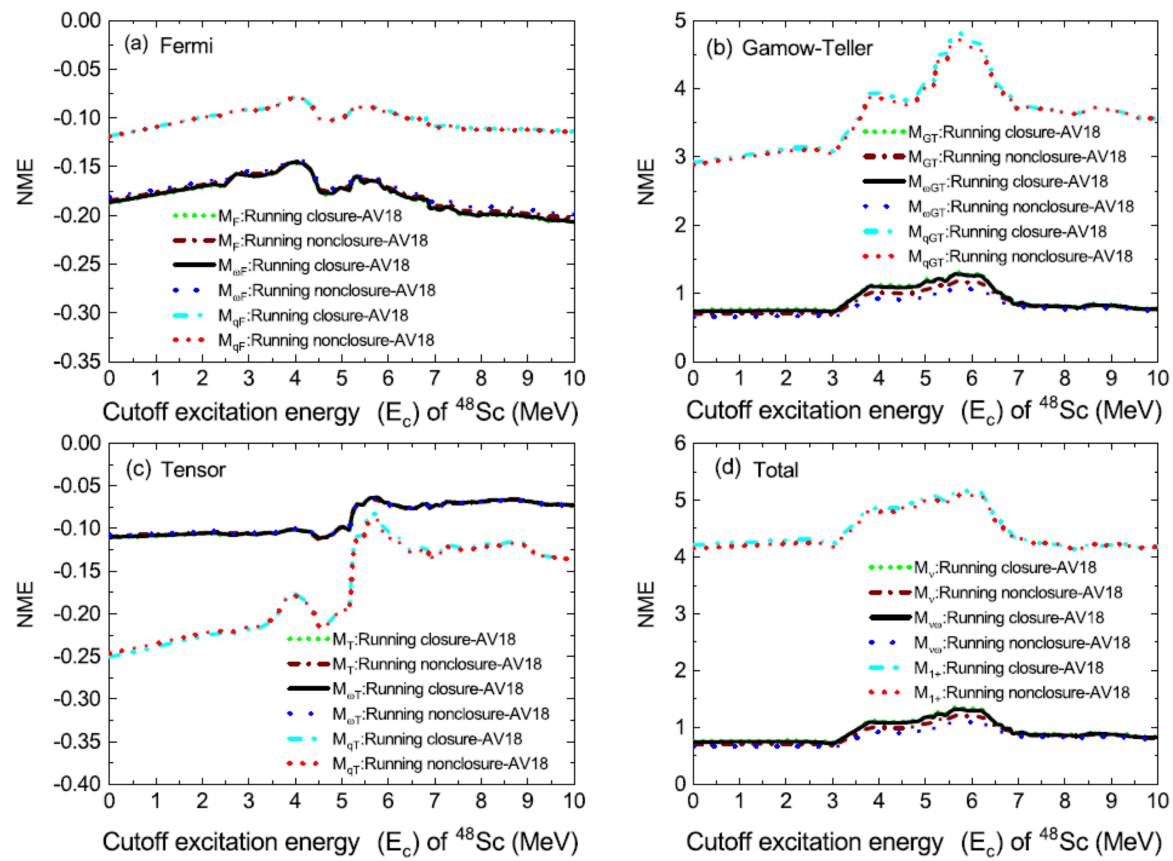
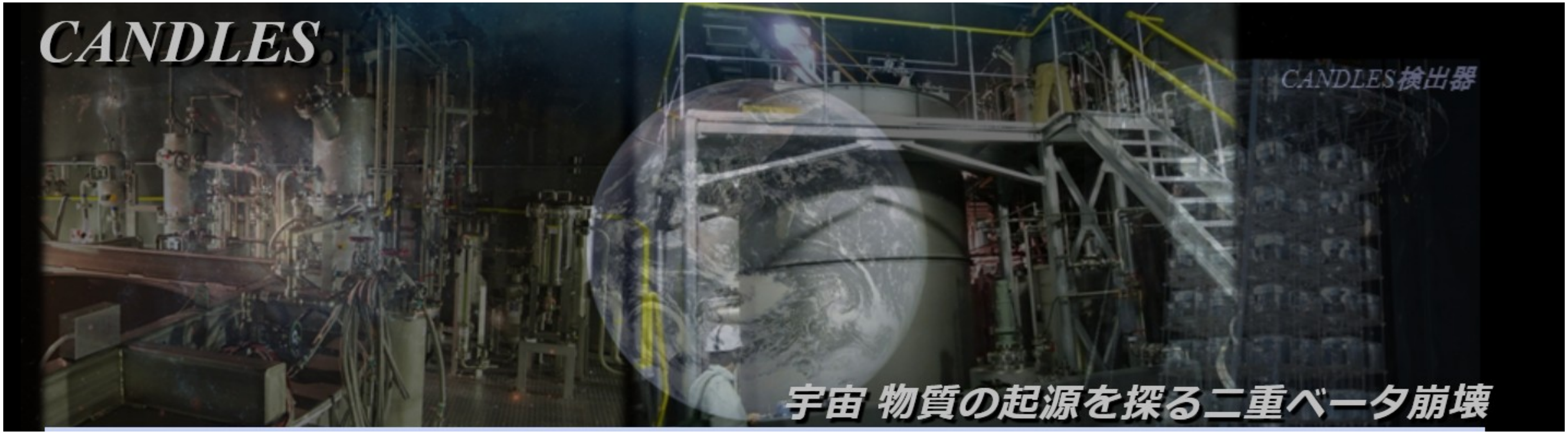


FIG. 8. Variation of (a) Fermi, (b) Gamow-Teller, (c) tensor, and (d) total NMEs for $0\nu\beta\beta$ ($m_{\beta\beta}$ and λ mechanisms) of ^{48}Ca with cutoff
citation energy (E_c) of states of virtual intermediate nucleus ^{48}Sc. NMEs are calculated with total GXPF1A interaction for AV18 SRC
arametrization in the running closure and running nonclosure methods. For the running closure method, closure energy $\langle E \rangle = 0.5$ MeV

DBD of ^{48}Ca

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



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Large-Scale Shell-Model Analysis of the Neutrinoless $\beta\beta$ Decay of ^{48}Ca

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We present the nuclear matrix element for the neutrinoless double-beta decay of ^{48}Ca based on large-scale shell-model calculations including two harmonic oscillator shells (sd and pf shells). The excitation spectra of ^{48}Ca and ^{48}Ti, and the two-neutrino double-beta decay of ^{48}Ca are reproduced in good agreement to the experimental data. We find that the neutrinoless double-beta decay nuclear matrix element is enhanced by about 30% compared to pf-shell calculations. This reduces the decay lifetime by almost a factor of 2. The matrix-element increase is mostly due to pairing correlations associated with cross-shell sd-pf excitations. We also investigate possible implications for heavier neutrinoless double-beta decay candidates.

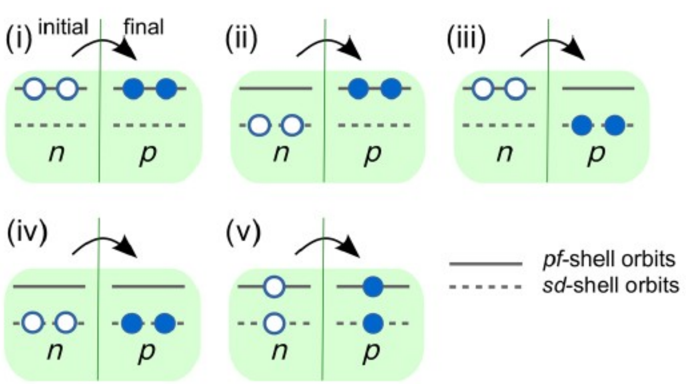
DOI: 10.1103/PhysRevLett.116.112502

TABLE I. NME value for the ^{48}Ca $0\nu\beta\beta$ decay. The pf-shell calculation with GXPF1B is compared to the $sdpf$ $2\hbar\omega$ results obtained with the SDPFMU-DB and SDPFMU interactions. Total values ($M^{0\nu}$) are shown together with Gamow-Teller ($M^{0\nu}_{GT}$), Fermi ($M^{0\nu}_{F}$), and tensor ($M^{0\nu}_{T}$) parts. Argonne- and CD-Bonn-type short-range correlations (SRC) are considered.

	GXPF1B				SDPFMU-DB				SDPFMU			
SRC	$M^{0\nu}_{GT}$	$M^{0\nu}_{F}$	$M^{0\nu}_{T}$	$M^{0\nu}$	$M^{0\nu}_{GT}$	$M^{0\nu}_{F}$	$M^{0\nu}_{T}$	$M^{0\nu}$	$M^{0\nu}_{GT}$	$M^{0\nu}_{F}$	$M^{0\nu}_{T}$	$M^{0\nu}$
None	0.776	−0.216	−0.077	0.833	0.997	−0.304	−0.067	1.118	0.894	−0.291	−0.068	1.007
CD-Bonn	0.809	−0.233	−0.074	0.880	1.045	−0.327	−0.065	1.183	0.939	−0.313	−0.065	1.068
Argonne	0.743	−0.213	−0.075	0.801	0.953	−0.300	−0.065	1.073	0.852	−0.288	−0.068	0.963

TABLE II. NME decomposition of Eq. (4), for a $sdpf$ $2\hbar\omega$ SDPFMU-DB calculation without short-range correlations. The total value is shown along with the contributions of $J^\pi = 0^+$ and all remaining pairs.

	$\mathcal{M}^{0\nu}_{1}$	$\mathcal{M}^{0\nu}_{2}$	$\mathcal{M}^{0\nu}_{3}$	$\mathcal{M}^{0\nu}_{4}$	$\mathcal{M}^{0\nu}_{5}$
Total	0.915	0.168	0.269	0.220	−0.454
$J^\pi = 0^+$	4.193	0.364	0.379	0.255	0.000
$J^\pi = 0^-, J > 0$	−3.278	−0.196	−0.109	−0.035	−0.454



NME values

S. Sarkar, YI, P. K. Raina, Phys. Rev. C 2020

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

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	x 1/2	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

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

*1 (std)

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

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

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

NME values

we have found
the large WR-WL effect

almost 2 times larger than WL-WL

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

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

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

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

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

$$f_F(q,r) = g_V^2(q^2) j_0(qr), \quad (16)$$

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

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

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

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

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

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

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

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

Not calculated in
Horoi, Neascu, PRC 2018

Heavy neutrino potential (by focusing on tensor part)

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

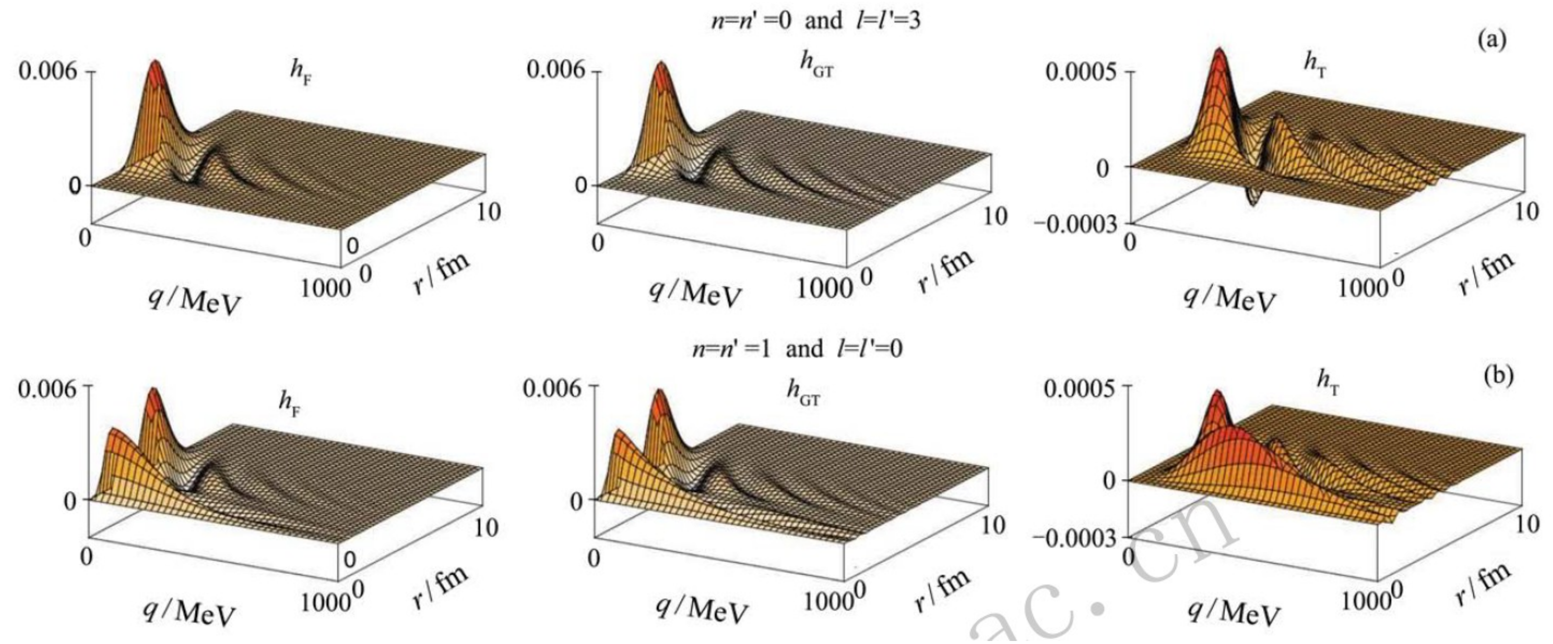
J. D. Vergados, H. Ejiri, and F. Simkovic, Rep. Prog. Phys. 75, 106301 (2012)
M. Horoi, Phys. Rev. C 87, 014320 (2013)

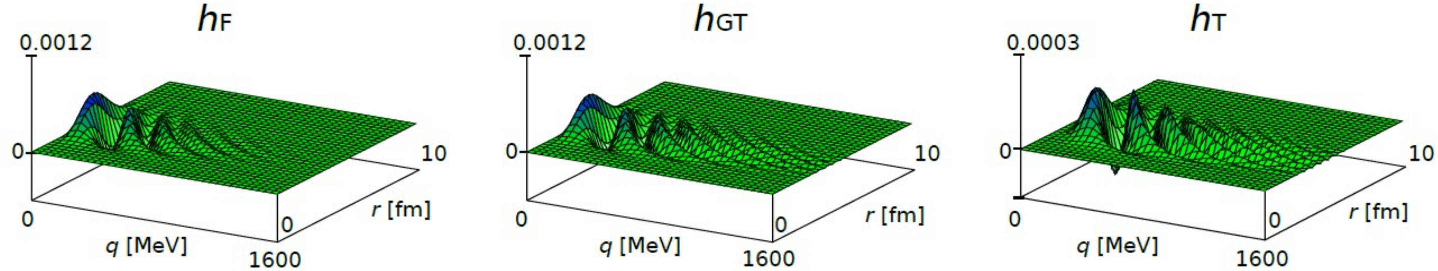
To be compared to ...

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

Y. Iwata, PoS INPC (2016)

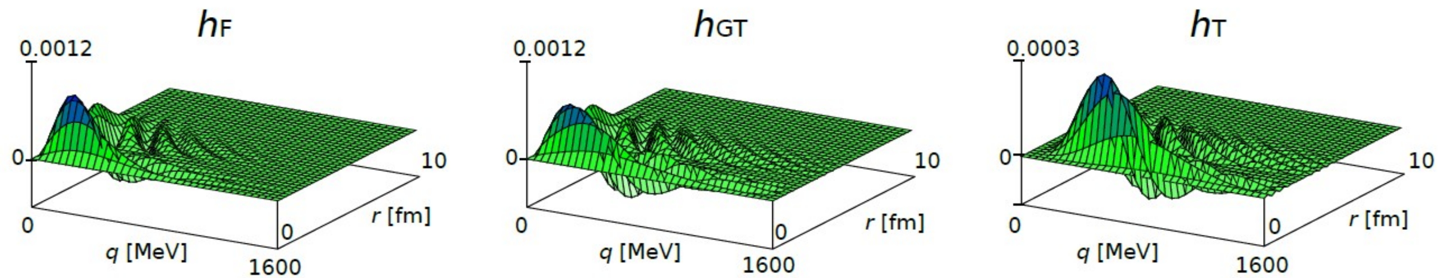
Light neutrino (standard mechanism)





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

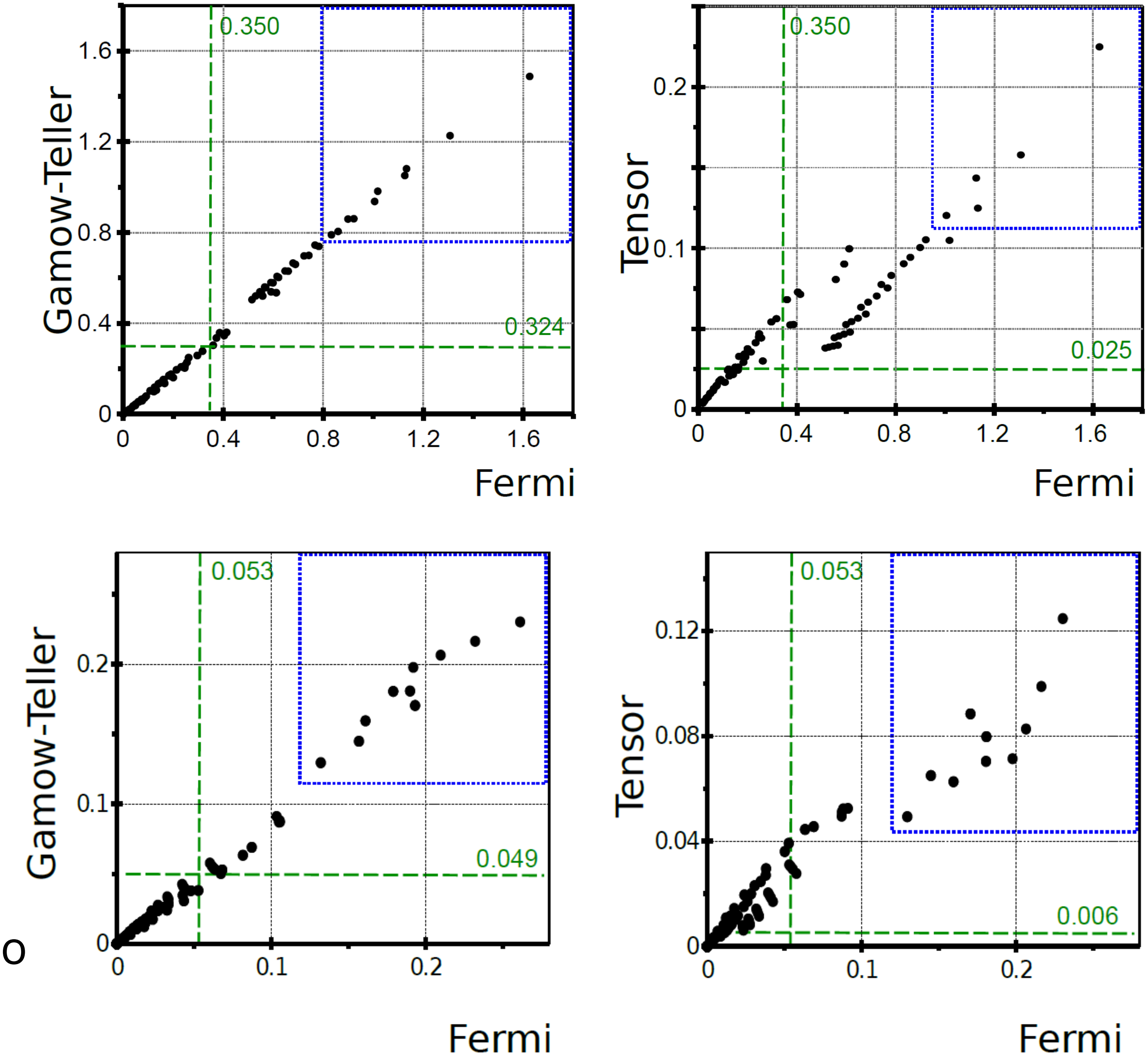
Heavy neutrino



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

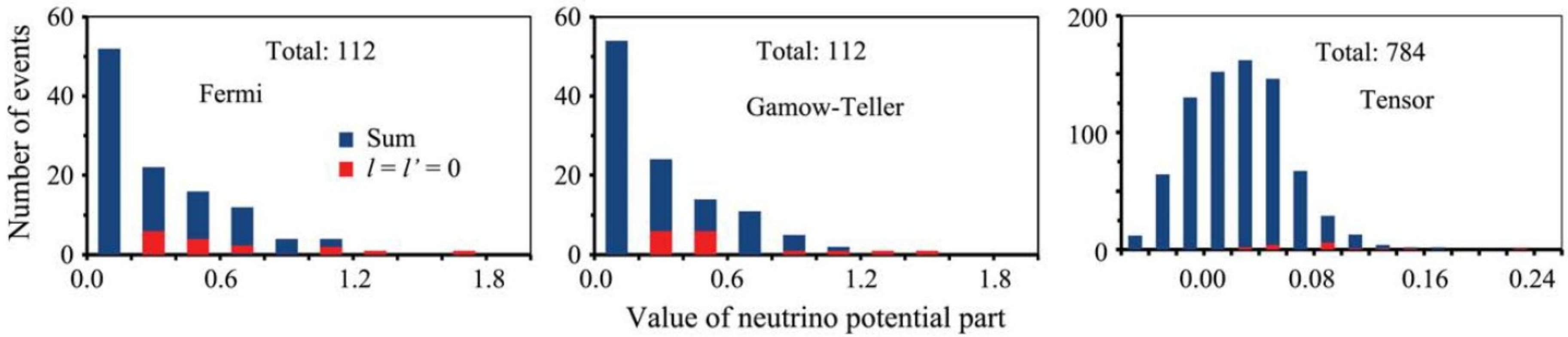
Light neutrino (standard mechanism)

Heavy neutrino



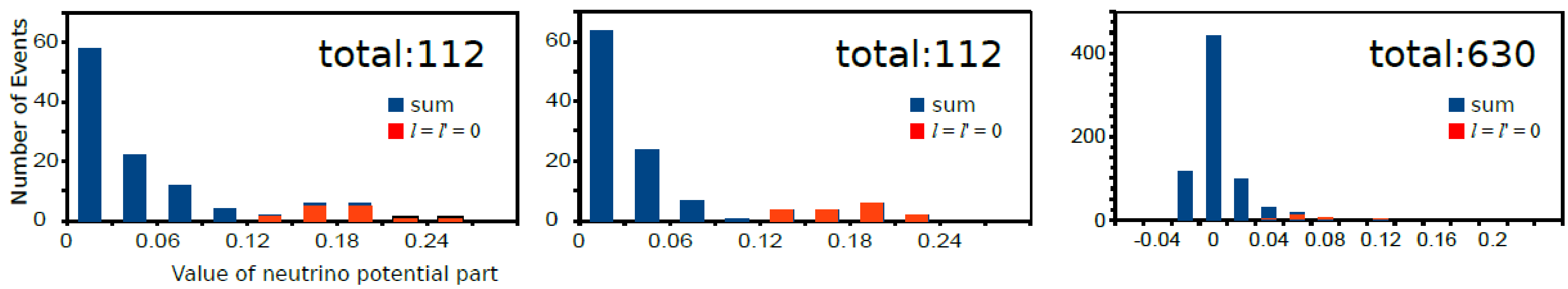
Light neutrino (standard mechanism)

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



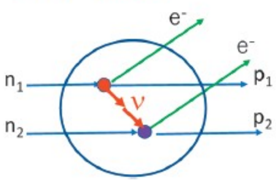
Heavy neutrino

Fermi Gamow-Teller Tensor

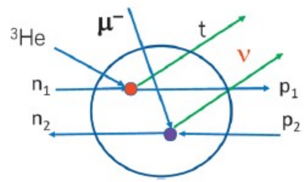


Relation to nuclear structure (charge exchange, 2ν process)

二重ベータ崩壊：



荷電交換反応：



◆◆◆◆ 解説 ◆◆◆◆

ニュートリノの原子核レスポンス
——二重ベータ崩壊と超新星ニュートリノの解明に向けて

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PHYSICAL REVIEW LETTERS **120,** 142502 (2018)

Double Gamow-Teller Transitions and its Relation to Neutrinoless $\beta\beta$ Decay

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(Received 1 September 2017; revised manuscript received 22 December 2017; published 5 April 2018)

We study the double Gamow-Teller (DGT) strength distribution of ^{48}Ca with state-of-the-art large-scale nuclear shell model calculations. Our analysis shows that the centroid energy of the DGT giant resonance depends mostly on the isovector pairing interaction, while the resonance width is more sensitive to isoscalar pairing. Pairing correlations are also key in neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay. We find a simple relation between the centroid energy of the ^{48}Ca DGT giant resonance and the $0\nu\beta\beta$ decay nuclear matrix element. More generally, we observe a very good linear correlation between the DGT transition to the ground state of the final nucleus and the $0\nu\beta\beta$ decay matrix element. The correlation, which originates on the dominant short-range character of both transitions, extends to heavier systems including several $\beta\beta$ emitters and also holds in energy-density functional results. Our findings suggest that DGT experiments can be a very valuable tool to obtain information on the value of $0\nu\beta\beta$ decay nuclear matrix elements.

DOI: 10.1103/PhysRevLett.120.142502

PHYSICAL REVIEW LETTERS **122,** 192501 (2019)

Precision Analysis of the ^{136}Xe Two-Neutrino $\beta\beta$ Spectrum in KamLAND-Zen and Its Impact on the Quenching of Nuclear Matrix Elements

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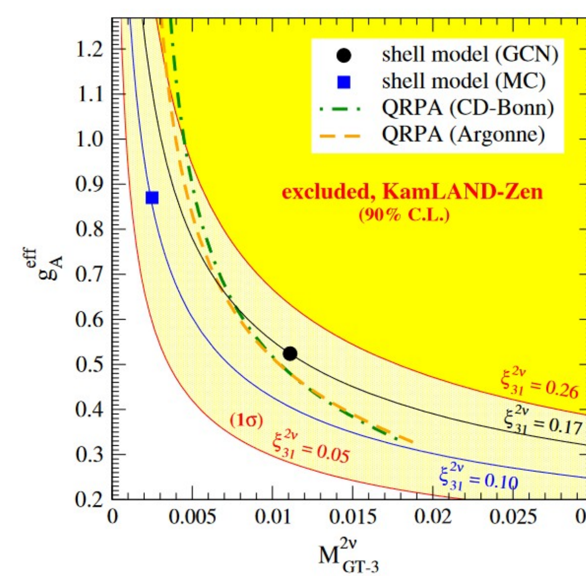
(KamLAND-Zen Collaboration)



Vicinity of ^{76}Ge, ^{82}Se, ^{90}Br

- two neutrino DBD

- single beta decay

- Gamow-Teller transition

Summary

frontiers

Interacting shell model calculations for neutrinoless double beta decay of ^{82}Se with left-right weak boson exchange

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Calculation in progress

^{48}Ca **Finished →η mechanism**

^{76}Ge early 2023

^{82}Se **Finished**

^{136}Xe 2022

Our package

- non-closure approx.
- tensor part included
- full expression of Npot. (left-right symmetric)
- parallel with two-neutrino DBD