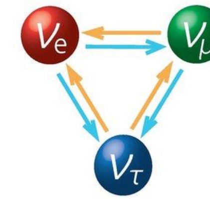
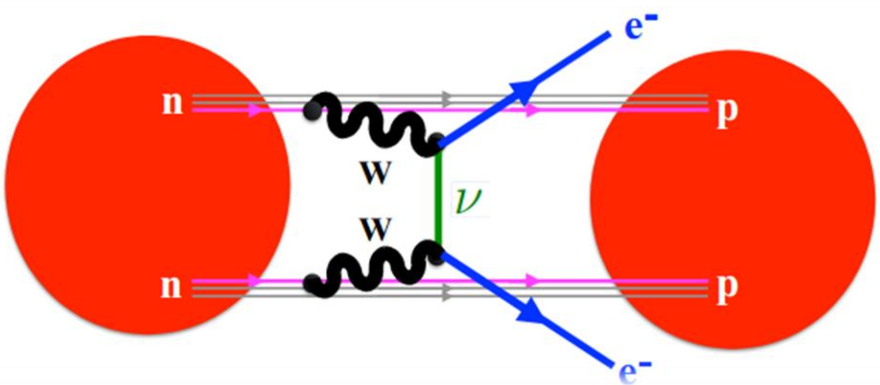
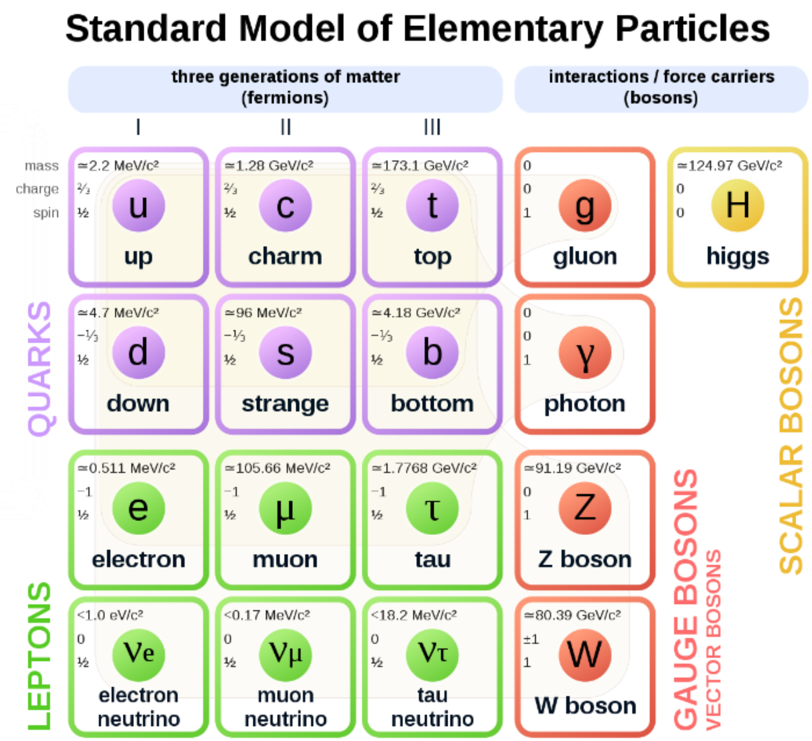


二重β崩壊の核行列要素





岩田順敬

大阪経済法科大学

Outlines

Neutrinoless double beta decay (0νββ)

⇓

Nuclear matrix element (NME)

⇓

International NME research CORE

Absolute Majorana Neutrino Masses

Decay rate of $0\nu\beta\beta$

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{\frac{1}{2}}} = G^{0\nu}(Q,Z)\left|m_{\beta\beta}\right|^2 |M^{0\nu}|^2$$

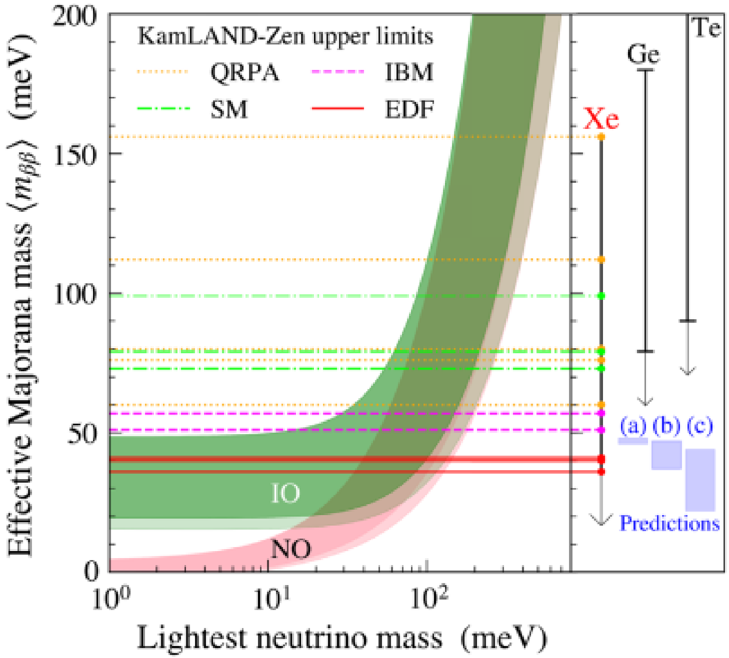
Majorana neutrino mass($m_{\beta\beta}$):

$$m_{\beta\beta} = \sum_i U_{ei}^2\, m_i$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \times \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{13}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{13}} & 0 & c_{13}\end{pmatrix}$$

$$\times \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \times \begin{pmatrix}e^{1/2i\alpha_1} & 0 & 0\\ 0 & e^{1/2i\alpha_2} & 0\\ 0 & 0 & 1\end{pmatrix}$$



Where, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$,
$0 \le \theta_{ij} \le \pi/2, 0 \le \delta_{13} \le 2\pi$, α_1 and α_2 are Majorana CP-violating phases.

Upper limit for $m_{\beta\beta}$ of 36-156 meV has been determined from $0\nu\beta\beta$ decay experiment of ^{136}Xe at KamLAND-Zen (PHYSICAL REVIEW LETTERS 130, 051801 (2023)) with lower limit of $T^{0\nu}_{1/2}$ 2.3×10^{26} yr using different nuclear matrix elements

Neutrinoless Double Beta Decay $(0\nu\beta\beta)$

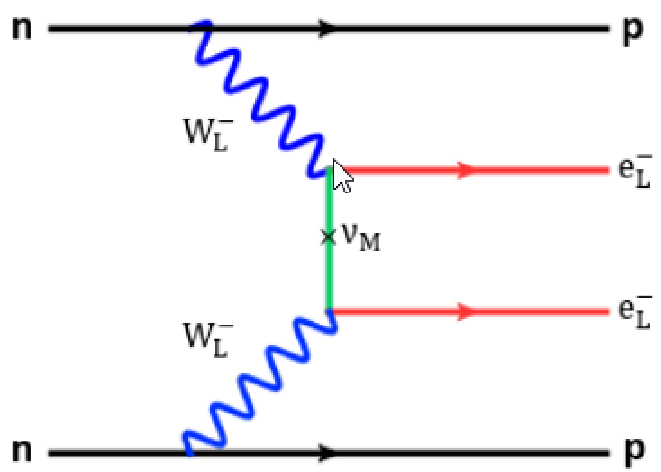


Fig1: Feynman diagram for light neutrino exchange $0\nu\beta\beta$

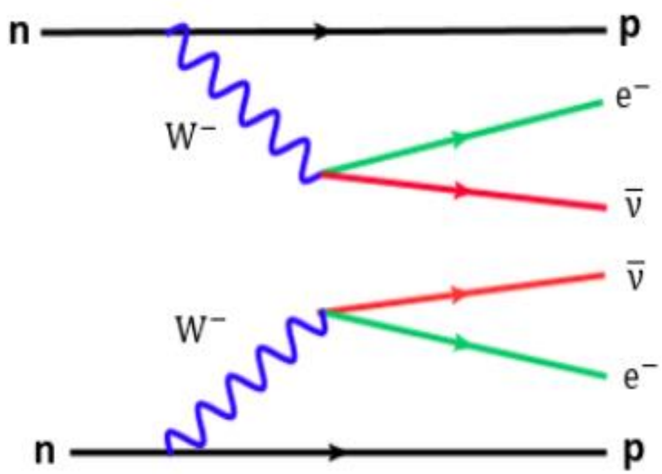
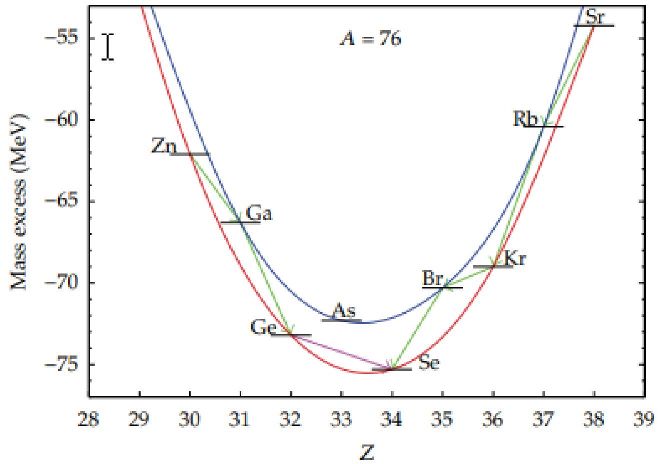


Fig 3: Feynman diagram for two-neutrino double beta decay

Neutrinoless Double Beta decay

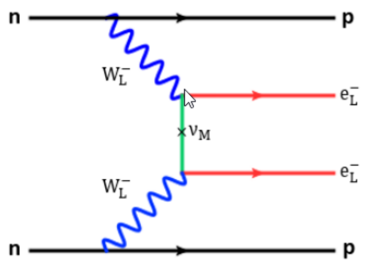
Two-Neutrino Double Beta decay

Observed in the experiment



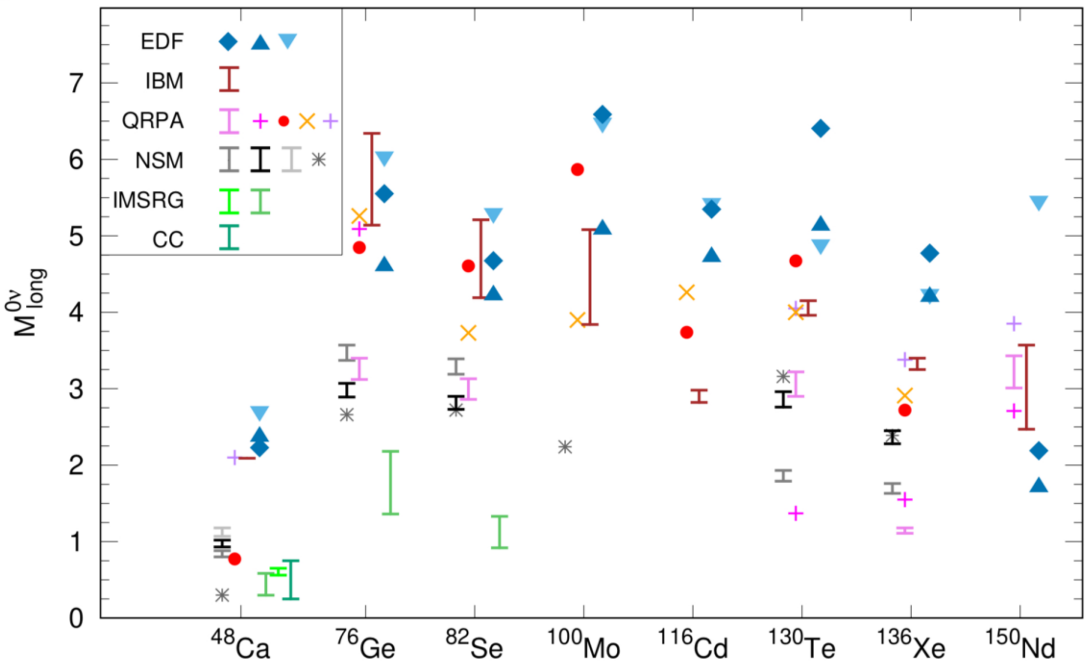
Decay Rate

Decay rate of 0νββ



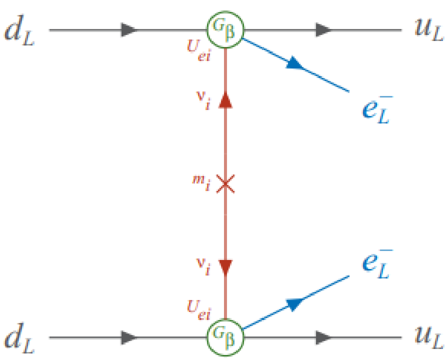
$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{\frac{1}{2}}} = G^{0\nu}(Q,Z)\left|m_{\beta\beta}\right|^2 |M^{0\nu}|^2$$

Large difference in nuclear matrix element calculations: factor ~ 3

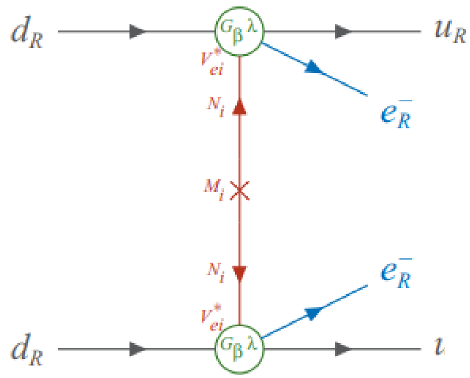


Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

Recent Topic: Left-Right Symmetric Mechanisms of 0νββ decay



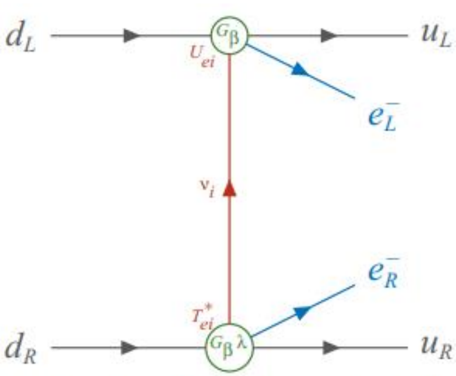
(a) Light neutrino exchange for purely LH currents. Diagram $\propto \eta_m$ arising from $j_L J_L^\dagger j_L J_L^\dagger$ term.



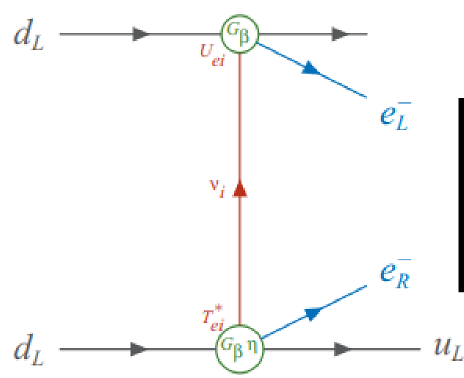
(b) Heavy neutrino exchange for purely RH current. Diagram $\propto \eta_N$ arising from $j_R J_R^\dagger j_R J_R^\dagger$ term.

If we consider all the diagrams of $0\nu\beta\beta$ decay in left-right symmetric model, the decay rate can be written as

$$\left[T_{1/2}^{0v}\right]^{-1} = g_A^4 \left[C_m |\eta_m|^2 + C_N |\eta_N|^2 + C_\lambda |\eta_\lambda|^2 + C_\eta |\eta_\eta|^2 \right.$$
$$+ C_{mN}|\eta_m||\eta_N|\cos(\phi_m - \phi_N) + C_{m\lambda}|\eta_m||\eta_\lambda|\cos(\phi_m - \phi_\lambda)$$
$$+ C_{m\eta}|\eta_m||\eta_\eta|\cos(\phi_m - \phi_\eta) + C_{N\lambda}|\eta_N||\eta_\lambda|\cos(\phi_N - \phi_\lambda)$$
$$+ C_{N\eta}|\eta_N||\eta_\eta|\cos(\phi_N - \phi_\eta) + C_{\lambda\eta}|\eta_\lambda||\eta_\eta|\cos(\phi_\lambda - \phi_\eta)$$



(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.

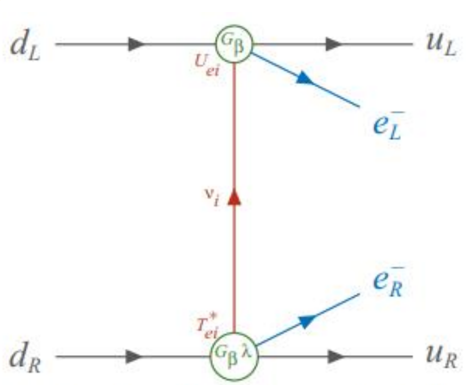
We aim to calculate all relevant nuclear matrix elements using closure and nonclosure approach

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

Recent Topic: Left-Right Symmetric Mechanisms of 0νββ decay
λ - mechanism

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. (Arnold et al., 2005) for ^{82}Se and from Ref. (Arnold et al., 2016) for ^{48}Ca. All results are for AV18 type SRC parameterizaionparameterization. We have assumed CP conservation (ψ =0). The results are compared with QRPA calculations for λ mechanism of Ref. (Šimkovic et al., 2017).

Quantity	^{82}Se	^{82}Se Ref. Šimkovic et al. (2017)	^{48}Ca	^{48}Ca Ref. Šimkovic et al. (2017)
$T_{1/2}^{0\nu-exp}$ [Years]	2.5×10^{23}	2.5×10^{23}	2.0×10^{22}	2.0×10^{22}
C_{mm} [Years]$^{-1}$	31.21×10^{-14}	51.3×10^{-14}	4.06×10^{-14}	2.33×10^{-14}
$C_{m\lambda}$ [Years]$^{-1}$	10.46×10^{-14}	-27.0×10^{-14}	3.37×10^{-14}	-1.04×10^{-14}
$C_{\lambda\lambda}$ [Years]$^{-1}$	36.19×10^{-14}	150.0×10^{-14}	5.39×10^{-14}	10.1×10^{-14}
$m_{\beta\beta}$ [eV]	1.83	1.43	17.92	23.7
η_λ	3.32×10^{-6}	1.63×10^{-6}	30.44×10^{-6}	22.30×10^{-6}



(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.

λ - mechanism

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ORIGINAL RESEARCH
published: 19 November 2021
doi: 10.3389/fspas.2021.727880

Interacting Shell Model Calculations for Neutrinoless Double Beta Decay of ^{82}Se With Left-Right Weak Boson Exchange

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Nuclear Matrix Element(NME) $M^{0\nu}$

$$M^{0\nu} = M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F + M^{0\nu}_T$$

- F- Fermi
- GT- Gamow-Teller
- T- Tensor
- g_V and g_A are vector and axial vector constant

$$M^{0\nu}_\alpha = \langle f | \tau_{-1}\tau_{-2}\, O^{\alpha}_{12} | i \rangle \quad \alpha = (F, GT, T)$$

0νββ transition operators

- Fermi Type: $O^F_{12} = S_F H_F(r) = H_F(r)$
- Gamow Teller type:

$$O^{GT}_{12} = S_{GT} H_{GT}(r) = \vec{\sigma}_1 . \vec{\sigma}_2 H_{GT}(r)$$

- Tensor Type:

$$O^T_{12} = S_T H_T(r) = [3(\vec{\sigma}_1 . \hat{r})(\vec{\sigma}_2 . \hat{r}) - \vec{\sigma}_1 . \vec{\sigma}_2] H_T(r)$$

Models of Nuclear Matrix Element calculations

- **Nuclear Shell Model (NSM) (We use this)**
- Quasiparticle Random Phase Approximation (QRPA)
- Projected Hartree Fock Bogliovob Method (PHFB)
- Interacting Boson Model 2 (IBM2)
- Energy Density Functional Theory (EDF)

Shell structure of nucleus

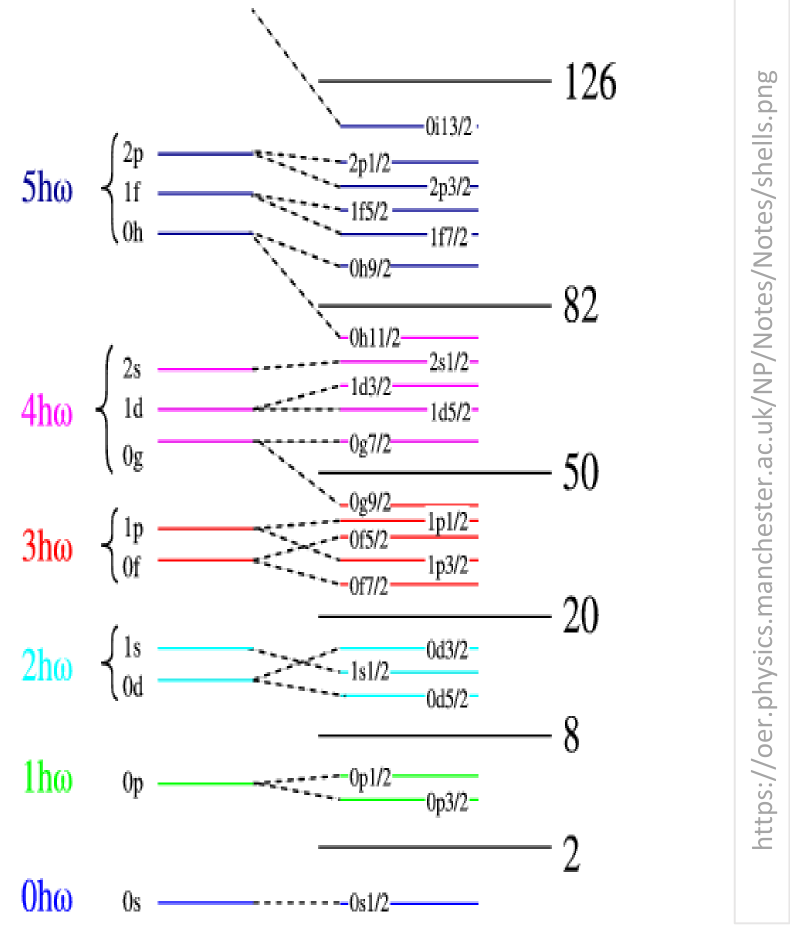

Fig 3: Nuclear shell structure

Method: Running nonclosure and closure

Here....Neutrino potential are calculated explicitly in terms of excitation energy of ^{48}Sc

$$H_\alpha(r, E_k^*) = \frac{2R}{\pi} * \int_0^\infty \frac{1}{q + E_0 + E_k^*} j_p(qr) g_\alpha(q) q dq$$

$$\langle n'l'|H_\alpha(r, E_k^*)|nl\rangle = \int_0^\infty R_{n'l'} R_{nl} r^2 dr * H_\alpha(r, E_k^*)$$

Closure approximation

$$E_0 + E_k^* = \langle E\rangle$$

Nonclosure Closure approximation

$$E_0 + E_k^* \rightarrow 1.9\ \text{MeV} + E_k^*$$

Explicit Form of NME in running nonclosure method

$$M^{0\nu}_{\alpha-\text{running nonclosure}}(E) = \sum_{k1' k_2' k_1 k_2 J J_k} \sum_{E_k^* \le E_C} \sqrt{(2J_k + 1)(2J_k + 1)(2J + 1)} \times (-1)^{j_{k1} + j_{k2} + J} \begin{Bmatrix} j_1 & j_2 & J_k \\ j_4 & j_3 & J \end{Bmatrix} \times \text{OBTD}(k, f, k_1', k_2', J_k) \times \text{OBTD}(k, i, k_1, k_2, J_k) \langle k_1' k_2' : J \left|\left| \tau_{-1}\tau_{-2}\mathcal{O}_{12}^{0\nu} \right|\right| k_1 k_2\rangle$$

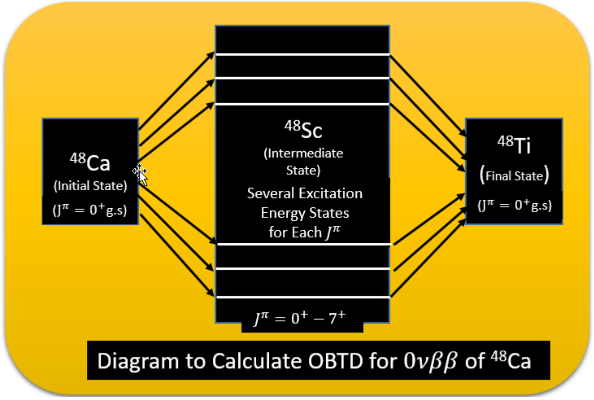

Fig 20: Schematic diagram to calculate OBTD

$$\text{OBTD}(k, f, k_1', k_2', J_k) = \frac{\langle k \left|\left| \left[a_{k_1}^+ \otimes \tilde{a}_{k_1'}\right]_{J_k} \right|\right| f\rangle}{\sqrt{2J_k + 1}}$$

Recent Trends in Theoretical NME research

- Two-neutrino double beta decay within the mapped IBM
- Modeling neutrinoless double-beta decay with operators from chiral effective field theory
- Impact of isovector pairing fluctuations on neutrinoless double-βdecay in MR-CDFT
- Improvement of reliability of nuclear matrix element of double-beta decay
- Neutrinoless DBD from valence-space in-medium similarity renormalization group
- Beta spectral shapes - A versatile tool for probing weak interactions
- Neutrinoless double-beta decay nuclear matrix elements: overview and future directions
- implication of ab initio no-core Monte Carlo Shell Model to double beta dacay
- Improved neutrinoless double-beta-decay matrix elements in the pnQRPA
- Anti-Neutrino Nuclear Responses by Ordinary Muon Capture: Status and Review
- Recent progress in the nuclear matrix element calculation using the FAM for QRPA
- High precision description of two neutrino double beta decay spectra
- Study of Neutrinoless Double Beta Decay in Nuclear Shell Model
- Impact from nuclear structure aspects on the neutrinoless double-beta decay
- Uncertainties of NME of neutrinoless DBD based on Skyrme QRPA model and beyond

Theoretical NME research network with EXPERIMENTALISTS

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Theoretical NME research network with EXPERIMENTALISTS

Summary

Neutrinoless double beta decay (0νββ)

⇓

Nuclear matrix element (NME)

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International NME research CORE