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Nuclear Matrix Elements for Neutrinoless Double-Beta Decay

Lotta Jokiniemi (she/her)
TRIUMF, Theory Department

TH Heavy Ion Coffee, CERN
8/1/2025

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Discovery, accelerated

Collaborators

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Universitat de Barcelona — D. Castillo, P. Soriano, J. Menéndez

Lawrence Livermore National Laboratory — K. Kravvaris

The University of North Carolina at Chapel Hill — B. Romeo

Jyväskylän Yliopisto / University of Jyväskylä — J. Kotila, J. Suhonen

Outline

Introduction

Corrections to $0\nu\beta\beta$-Decay Nuclear Matrix Elements

Correlations with Other Observables to Constrain the Matrix Elements

Summary and Outlook

Discovery, accelerated

Outline

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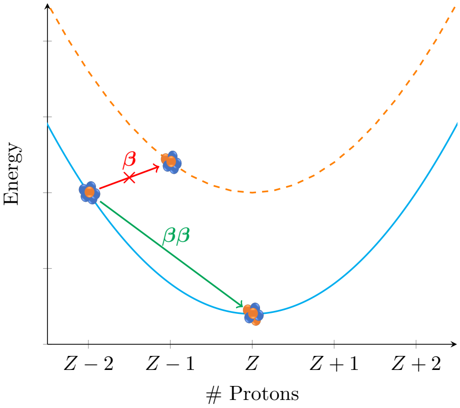
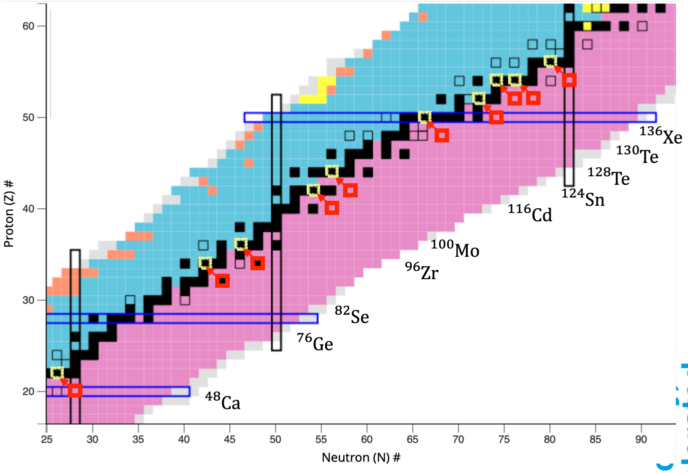
Double-Beta Decay



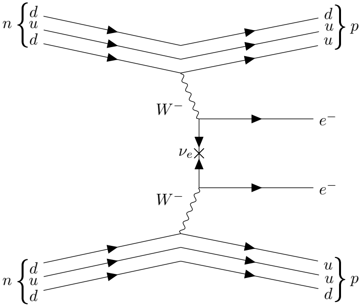


nndc.bnl.gov

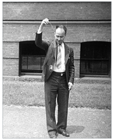
Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay

- **Violates lepton-number conservation**

$$(A,Z) \rightarrow (A,Z+2) + 2e^- \cancel{+2\bar{\nu}_e}$$



Maria Goeppert-Mayer *Ettore Majorana* *Wendell H. Furry*



$2\nu\beta\beta$ Majorana particles $0\nu\beta\beta$

1935 → 1937 → 1939 → …

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

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- Requires that **neutrinos are Majorana particles**

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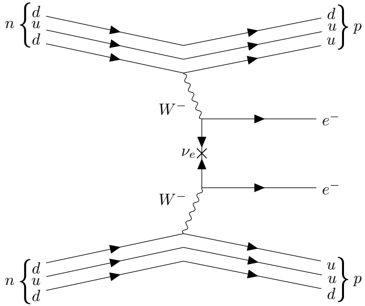


Maria Goeppert-Mayer

$2\nu\beta\beta$

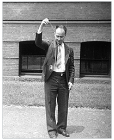
1935

Ettore Majorana

Majorana particles

1937

Wendell H. Furry



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

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- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ **years**

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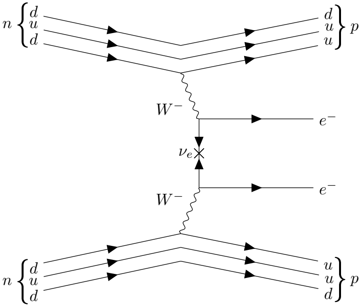

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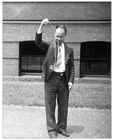

$2\nu\beta\beta$ | Majorana particles | $0\nu\beta\beta$

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Discovery, accelerated

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

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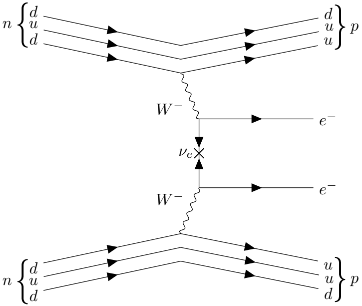
- Requires that **neutrinos are Majorana particles**
- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ **years**
  ($t_{1/2}^{2\nu} \approx 10^{20}$ years,
  age of the Universe $\approx 10^{10}$ years)

$$(A,Z) \rightarrow (A,Z+2) + 2e^- \cancel{+2\bar{\nu}_e}$$



Maria Goeppert-Mayer

$2\nu\beta\beta$

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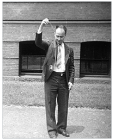
Majorana particles

Wendell H. Furry



$0\nu\beta\beta$

1935 → 1937 → 1939 → …

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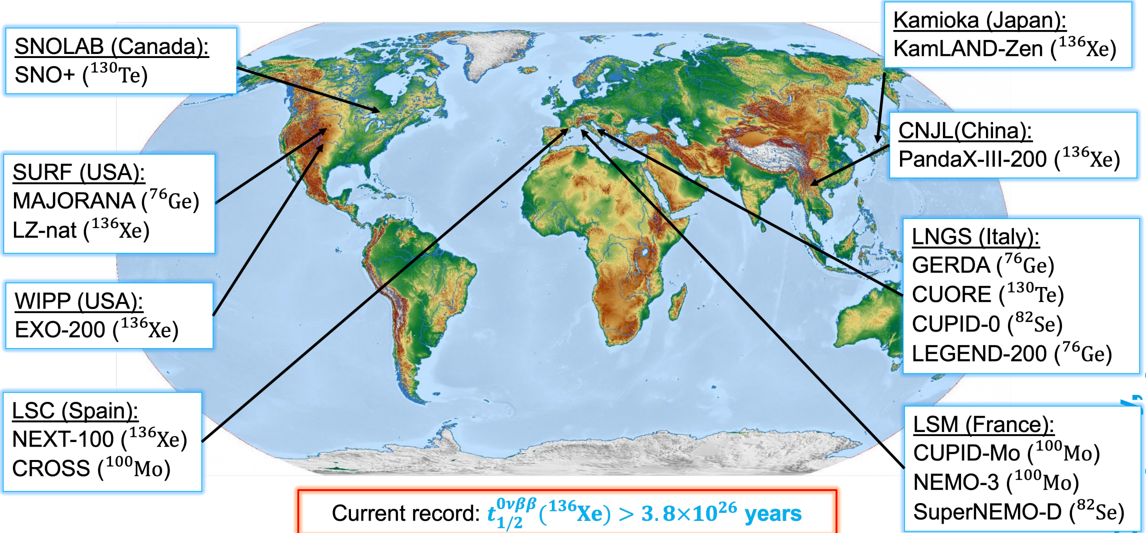
$0\nu\beta\beta$-Decay Experiments



Current record: $t_{1/2}^{0\nu\beta\beta}(^{136}\mathrm{Xe}) > 3.8\times10^{26}$ years

KamLAND-Zen, arXiv:2407:11438

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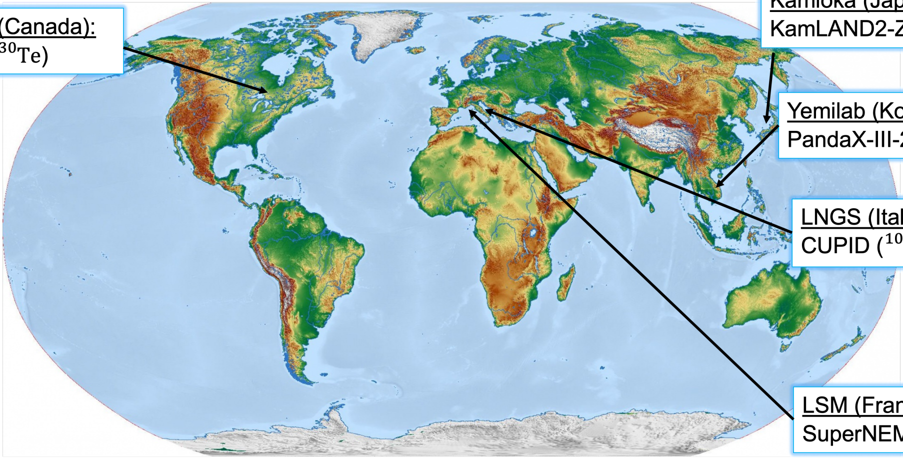
Next-Generation $0\nu\beta\beta$-Decay Experiments



SNOLAB (Canada):
SNO+II (^{130}Te)

Kamioka (Japan):
KamLAND2-Zen (^{136}Xe)

Yemilab (Korea):
PandaX-III-200 (^{136}Xe)

LNGS (Italy):
CUPID (^{100}Mo)

LSM (France):
SuperNEMO (^{82}Se)

+nEXO (^{136}Xe), LEGEND-1000 (^{76}Ge), NEXT-HD (^{136}Xe), Darwin (^{136}Xe), …

M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

Discovery, accelerated

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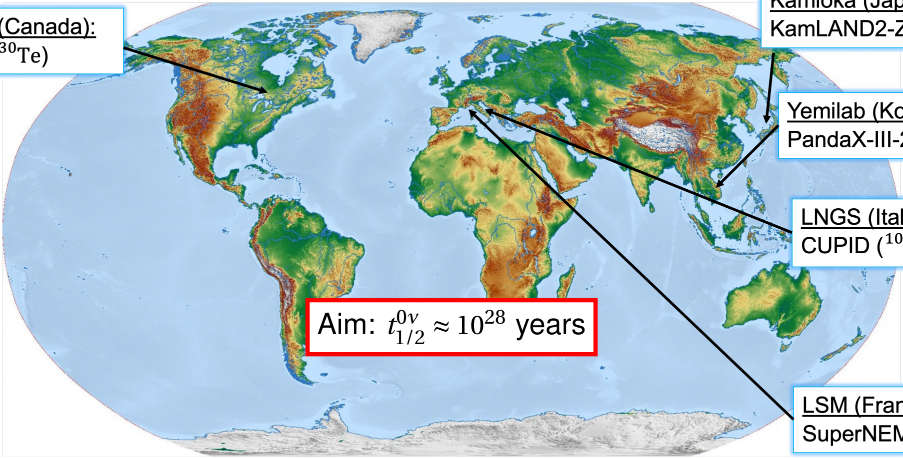

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Aim: $t_{1/2}^{0\nu} \approx 10^{28}$ years

+nEXO (^{136}Xe), LEGEND-1000 (^{76}Ge), NEXT-HD (^{136}Xe), Darwin (^{136}Xe), …

M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

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$0\nu\beta\beta$-Decay Half-Life

What would be measured

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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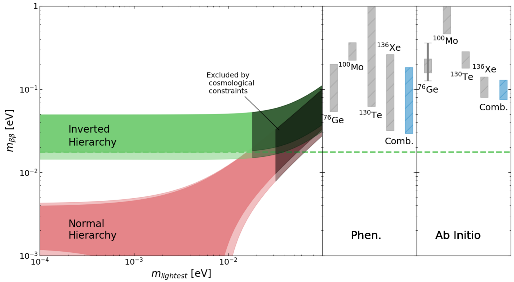
$0\nu\beta\beta$-Decay Half-Life

What would be measured

$$\frac{1}{t^{0\nu}_{1/2}} = g_A^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass

$m_{\beta\beta} = \sum_k (U_{ek})^2 m_k$



T. Shickele, LJ, A. Belley, J. D. Holt, in preparation

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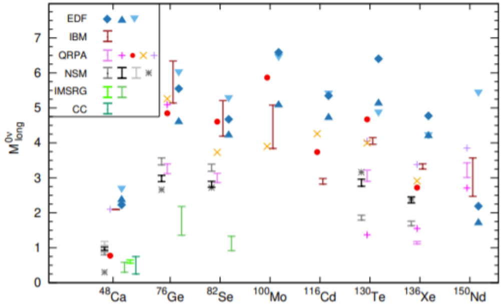
Nuclear matrix element



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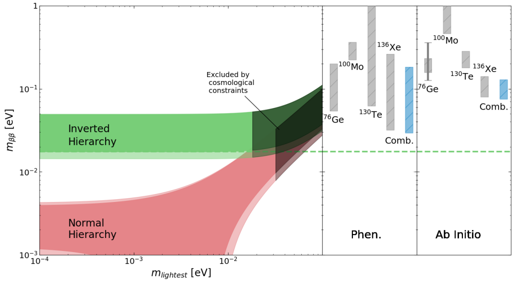

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Neutrino Masses

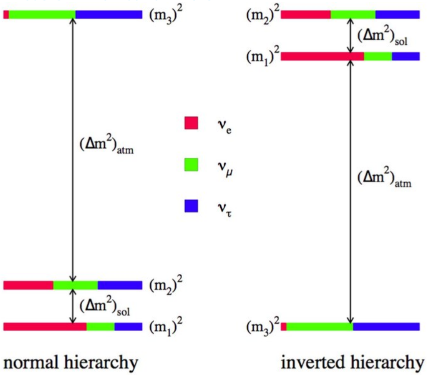
$$m_{\beta\beta} = \sum_k (U_{ek})^2 m_k$$

Neutrino mixing matrix:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Flavor eigenstates

Mass hierarchies



Discovery, accelerated

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Flavor eigenstates

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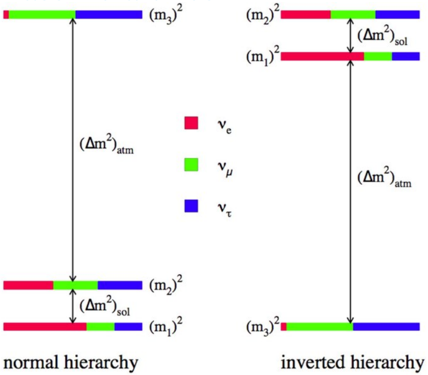

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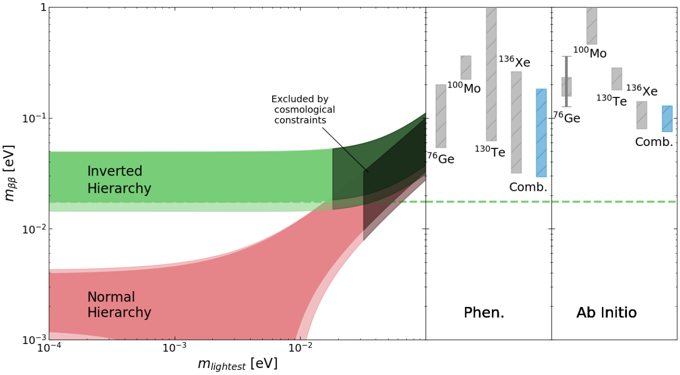
Effective Majorana Mass

$$m_{\beta\beta} = \frac{m_e}{g_A^2 |M^{0\nu}|} \frac{1}{\sqrt{G^{0\nu}\, t_{1/2}^{0\nu}}}$$



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Nuclear Matrix Element

Operator

$$2n \rightarrow 2p + 2e^-$$

$$M^{0\nu} = \langle \Psi_f^{(A)} || \mathcal{O}^{0\nu\beta\beta} || \Psi_i^{(A)} \rangle$$

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Initial state

Nuclear Matrix Element

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Final state

Initial state

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Final state *Initial state*

$$H\Psi^{(A)} = E\Psi^{(A)}\,, \; H = \sum_i \frac{p_i^2}{2m_i} + \sum_{i \neq i} V_{ij}^{2N} + \sum_{i \neq j \neq k} V_{ijk}^{3N}$$

Nuclear Matrix Element

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Schrödinger equation + *Nuclear Hamiltonian*

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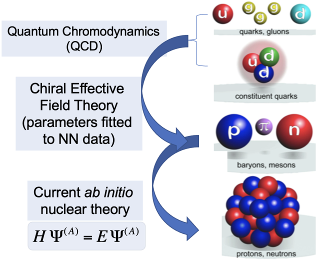
Nuclear Many-body Methods

$$\boxed{H^{(A)}\Psi^{(A)} = E^{(A)}\Psi^{(A)}}$$

- *Ab initio methods* (IMSRG, NCSM,...)



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Nuclear Many-body Methods

$$H^{(A)}\Psi^{(A)} = E^{(A)}\Psi^{(A)}$$

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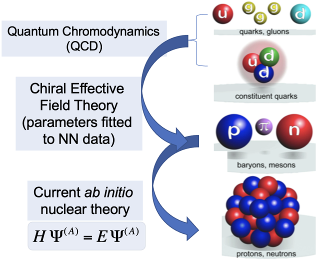
  - + **Aim to solve nuclear Schrödinger equation (SE) starting from interactions between nucleons**



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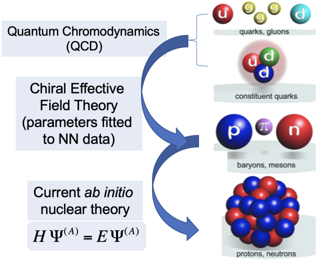

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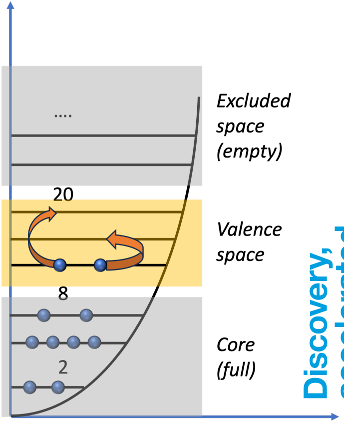

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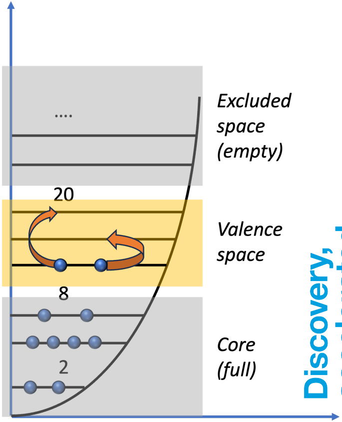

Discovery, accelerated

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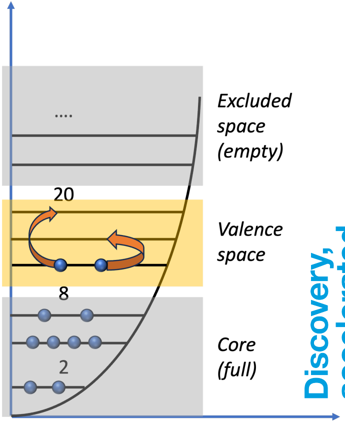

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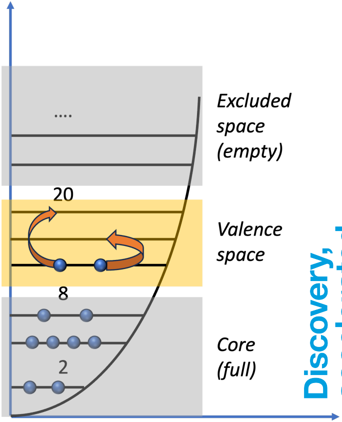

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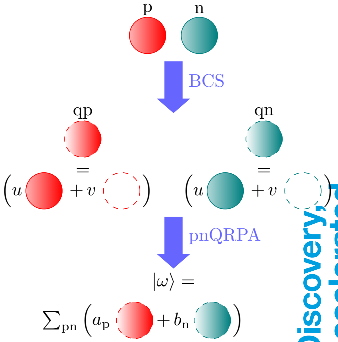

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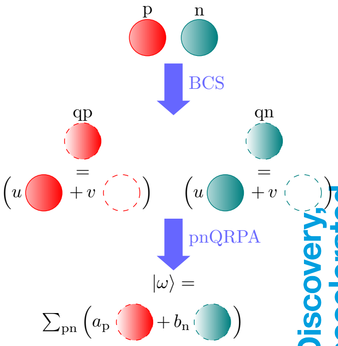

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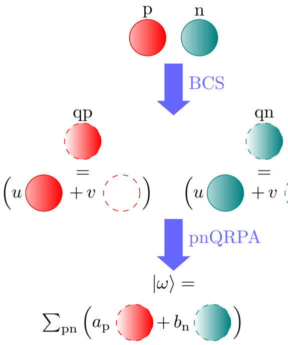

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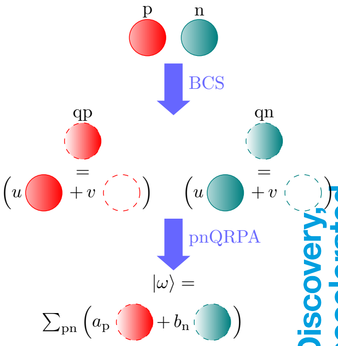

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- ...

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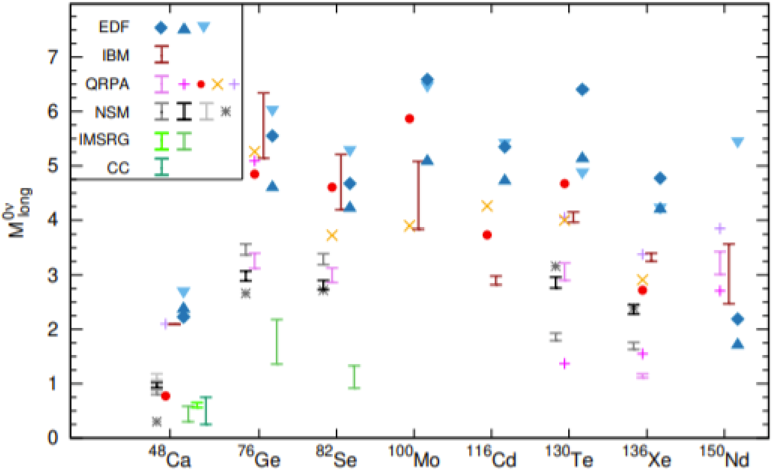
Different Many-body Methods Disagree



M. Agostini et al., Rev. Mod. Phys. ***95****, 025002 (2023)*

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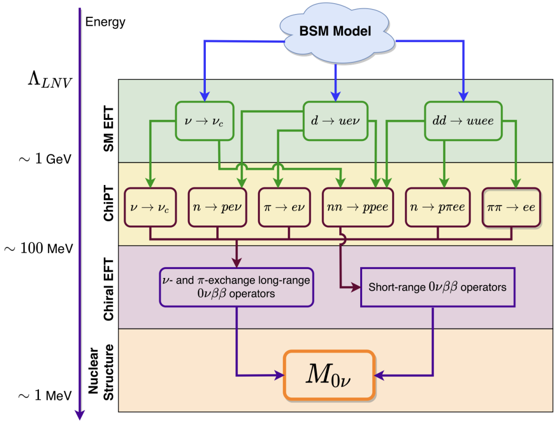
Effective Field Theory For $0\nu\beta\beta$ Decay



V. Cirigliano et al., J. Phys. G: Nucl. Part. Phys. 49, 120502 (2022)

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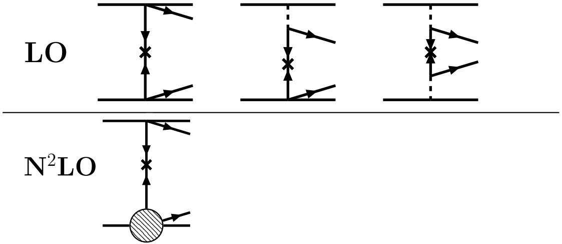
Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

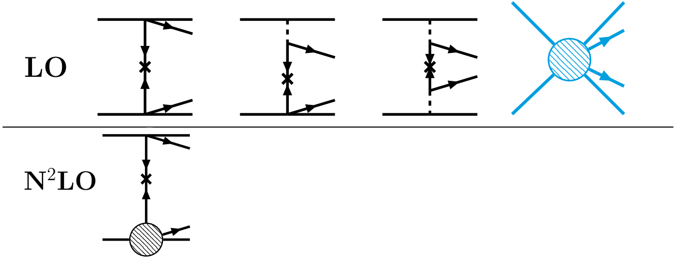
V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

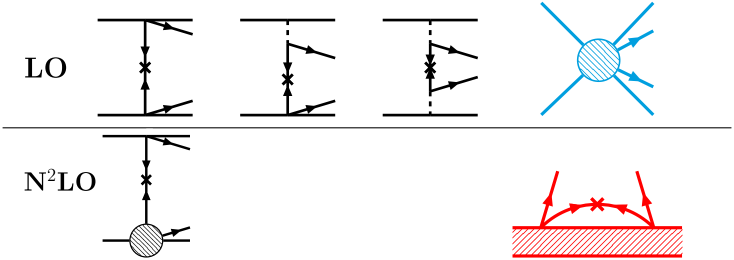


TRIUMF

Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left| M_L^{0\nu} + \boldsymbol{M_S^{0\nu}} + \boldsymbol{M_{\mathrm{usoft}}^{0\nu}} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

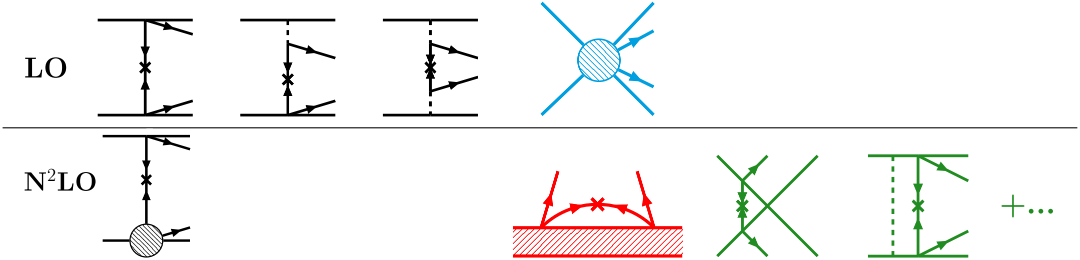


Discovery, accelerated

Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left| M_L^{0\nu} + M_S^{0\nu} + M_{\mathrm{usoft}}^{0\nu} + M_{\mathrm{N^2LO}}^{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



TRIUMF

Traditional $0\nu\beta\beta$-Decay Operators

$$M^{0\nu} = \frac{4\pi R}{g_{\mathbf{A}}^2} \int \mathbf{dx} \int \mathbf{dy} \int \frac{\mathbf{dk}}{(2\pi)^3} \frac{e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{y})}}{|\mathbf{k}|} \sum_n \frac{\langle f \big| J_\mu(\mathbf{x}) \,|n\rangle \,\langle n| \,J^\mu(\mathbf{y}) \,|i\rangle}{|\mathbf{k}| + E_n - \frac{1}{2}(E_i + E_f)}$$

Discovery, accelerated

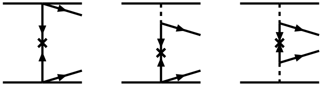
Traditional $0\nu\beta\beta$-Decay Operators

$$M^{0\nu} = \frac{4\pi R}{g_A^2} \int \mathrm{d}\mathbf{x} \int \mathrm{d}\mathbf{y} \int \frac{\mathrm{d}\mathbf{k}}{(2\pi)^3} \frac{e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{y})}}{|\mathbf{k}|} \sum_n \frac{\langle f | J_\mu(\mathbf{x}) | n\rangle \langle n | J^\mu(\mathbf{y}) | i\rangle}{|\mathbf{k}| + E_n - \frac{1}{2}(E_i + E_f)}$$

- Traditionally, the nuclear current includes the leading-order (LO) transition operators

$$\mathscr{J}^0 = \tau[g_V(0)]$$
$$\boldsymbol{J} = \tau[g_A(0)\boldsymbol{\sigma} - g_P(0)\boldsymbol{p}(\boldsymbol{p}\cdot\boldsymbol{\sigma})]$$

LO



Discovery, accelerated

Traditional $0\nu\beta\beta$-Decay Operators

$$M^{0\nu} = \frac{4\pi R}{g_A^2} \int \mathrm{d}\mathbf{x} \int \mathrm{d}\mathbf{y} \int \frac{\mathrm{d}\mathbf{k}}{(2\pi)^3} \frac{e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{y})}}{|\mathbf{k}|} \sum_n \frac{\langle f | J_\mu(\mathbf{x}) | n \rangle \langle n | J^\mu(\mathbf{y}) | i \rangle}{|\mathbf{k}| + E_n - \frac{1}{2}(E_i + E_f)}$$

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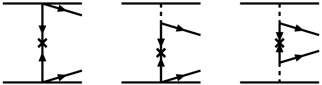
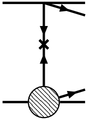
LO



- and next-to-next-to-leading-order (N^{2}LO) corrections absorbed into **form factors** and **induced weak-magnetism terms**

$$\mathscr{J}^0 = \tau\,[g_V(p^2)]$$
$$\boldsymbol{J} = \tau\left[g_A(p^2)\boldsymbol{\sigma} - g_P(p^2)\boldsymbol{p}(\boldsymbol{p}\cdot\boldsymbol{\sigma}) + i g_M(p^2)\frac{\boldsymbol{\sigma}\times\boldsymbol{p}}{2m_N}\right]$$

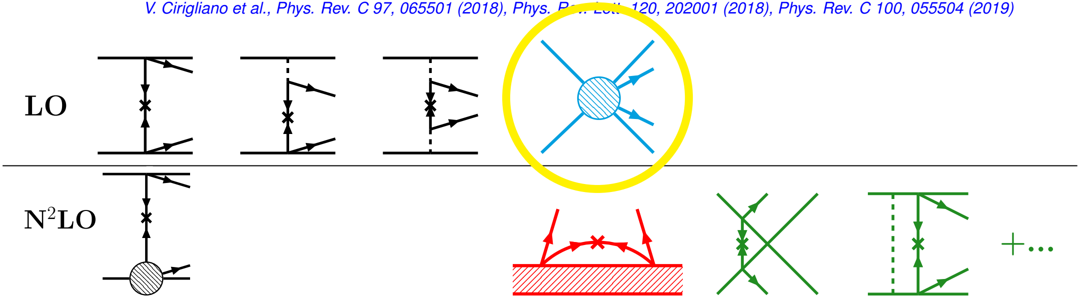
N^{2}LO



Leading-order short-range contribution to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu} + M_{N^2LO}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



Contact Term in pnQRPA and NSM

- The contact term reads

$$M_S^{0\nu} = \frac{2R}{\pi g_A^2}\langle 0_f^+ | \sum_{m,n} \tau_m^- \tau_n^- \int j_0(qr)\, h_S(q^2)\, q^2 \mathrm{d}q | 0_i^+ \rangle$$

with

$$h_S(q^2) = 2 g_\nu^{NN}\, e^{-q^2/(2\Lambda^2)}\,.$$

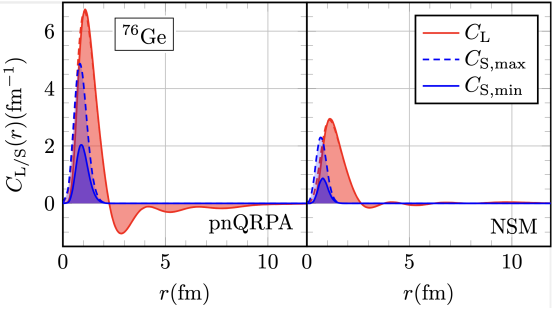
$$\int C_{L/S}(r)\mathrm{d}r = M_{L/S}^{0\nu}$$

In pnQRPA:

$M_S/M_L \approx 30\% - 80\%$

In NSM:

$M_S/M_L \approx 15\% - 50\%$



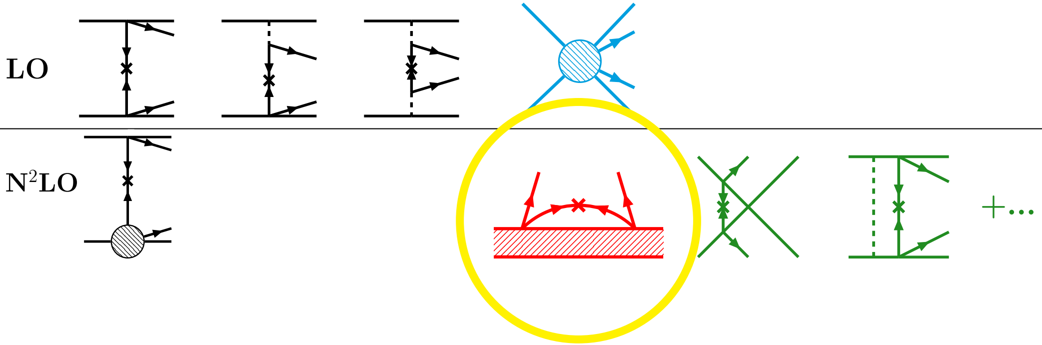
LJ, P. Soriano and J. Menéndez, Phys. Lett. B ***823****, 136720 (2021)*

Discovery, accelerated

Ultrasoft-neutrino contribution to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu} + M_{N^2LO}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

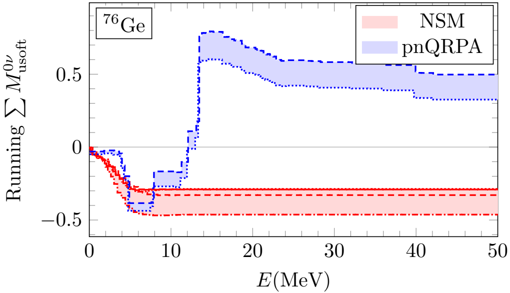


Ultrasoft Neutrinos in pnQRPA and NSM

- Contribution of ultrasoft neutrinos ($|\mathbf{k}| << k_F \approx 100$ **MeV**) to $0\nu\beta\beta$ decay:

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018)

$$M^{0\nu}_{\rm usoft} = -\frac{2R}{\pi}\sum_n \langle f||\sum_a \boldsymbol{\sigma}_a\tau_a^+||n\rangle\langle n||\sum_b \boldsymbol{\sigma}_b\tau_b^+||i\rangle \times (E_e+E_n-E_i)\left(\ln\frac{\mu_{\rm us}}{2(E_e+E_n-E_i)}+1\right)$$



D. Castillo, LJ, P. Soriano, J. Menéndez, Phys. Lett. B 860, 139181 (2025)

In pnQRPA:

$|M^{0\nu}_{\rm usoft}/M^{0\nu}_{\rm L}| \leq 30\%$

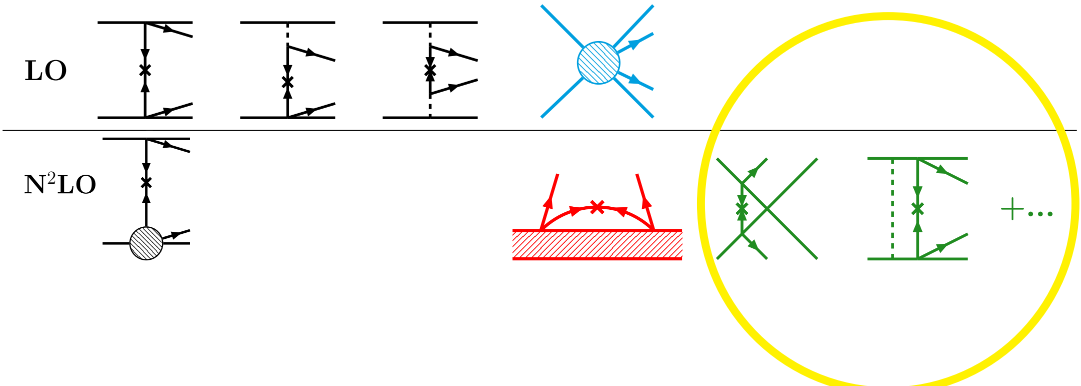
In NSM:

$|M^{0\nu}_{\rm usoft}/M^{0\nu}_{\rm L}| \leq 10\%$

N^2LO Loop Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left| M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu} + M_{N^2LO}^{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



N^2LO Loop Corrections in pnQRPA and NSM

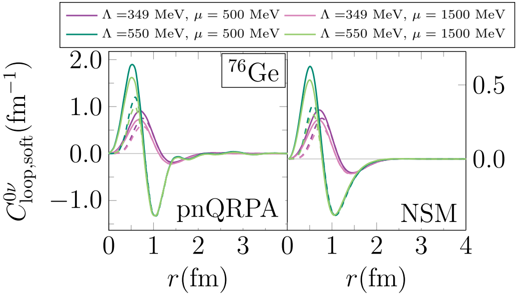
- The N^2LO loop corrections read as

$$M^{0\nu}_{\rm loops} = \frac{4R}{\pi g_A^2}\langle 0_f^+|\sum_{a,b}\tau_a^-\tau_b^-\int e^{-\frac{q^2}{2\Lambda^2}} j_u(qr)\, V^{(a,b)}_{\nu,2}\, q^2 {\rm d}q|0_i^+\rangle$$

with

$$V^{(a,b)}_{\nu,2} = V^{(a,b)}_{\rm VV} + V^{(a,b)}_{\rm AA} + \ln\frac{m_\pi^2}{\mu_{\rm us}^2} V^{(a,b)}_{\rm us} + V^{(a,b)}_{\rm CT}$$

$$\int C^{0\nu}_{\rm N^2LO}(r){\rm d}r = M^{0\nu}_{\rm loops}$$



In pnQRPA:

$|M_{\rm N^2LO}/M_{\rm L}| \approx 2\% - 10\%$

In NSM:

$|M_{\rm N^2LO}/M_{\rm L}| \approx 4\% - 10\%$

D. Castillo, LJ, P. Soriano, J Menéndez, Phys. Lett. B 860, 139181 (2025)

TRIUMF

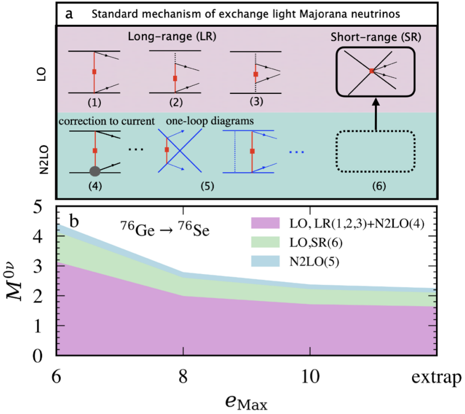
Similar effects found in *ab initio* studies

- In ^{76}Ge:

$$M_S^{0\nu}/M_L^{0\nu} \sim 40\% \,,$$

$$M_{\text{loop}}^{0\nu}/M_L^{0\nu} \sim 5\%^{a}$$

A. Belley et al. arXiv:2308.15634 (2023)



A. Belley et al. arXiv:2308.15634 (2023)

[a] I found some errors in the expressions

Discovery, accelerated

TRIUMF

Similar effects found in *ab initio* studies

- In ^{76}Ge:

$$M_S^{0\nu}/M_L^{0\nu} \sim 40\% ,$$

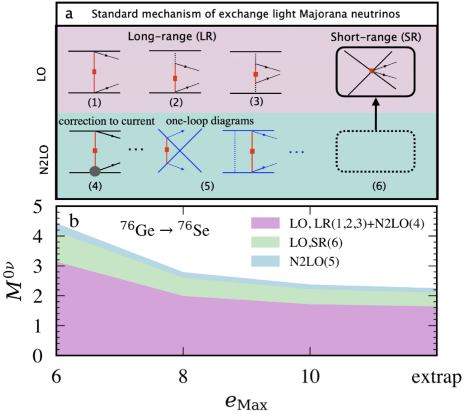
$$M_{loop}^{0\nu}/M_L^{0\nu} \sim 5\%^a$$

A. Belley et al. arXiv:2308.15634 (2023)

- In ^{130}Te and ^{136}Xe:

$$M_S^{0\nu}/M_L^{0\nu} \sim 20\% - 120\%$$

A. Belley et al. arXiv:2307.15156 (2023)



A. Belley et al. arXiv:2308.15634 (2023)

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[a] I found some errors in the expressions

Discovery, accelerated

Outline

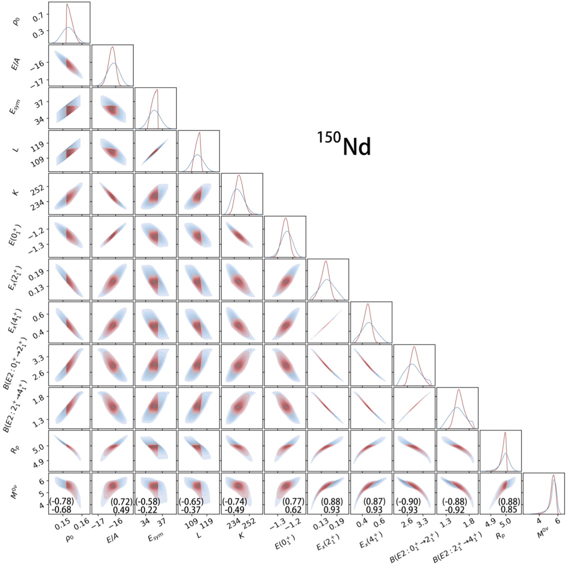
Introduction

Corrections to $0\nu\beta\beta$-Decay Nuclear Matrix Elements

Correlations with Other Observables to Constrain the Matrix Elements

Summary and Outlook

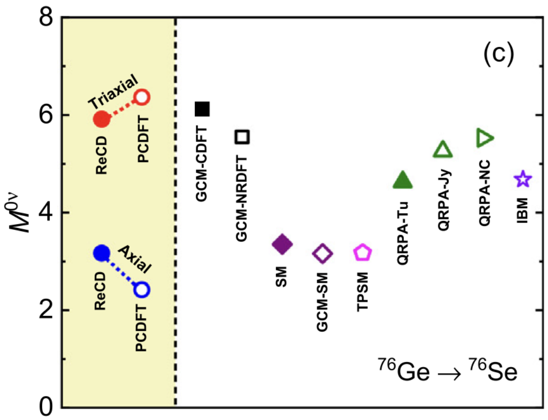
Correlations with Structure Observables



X. Zhang, C. C. Wang, C. R. Ding, and J. M. Yao, arXiv:2408:13209[nucl-th]

TRIUMF

Effect of Triaxial Deformation on $M^{0\nu}$ of ^{76}Ge



Y. Wang et al., Science Bulletin 69, 2017–2020 (2024)

Discovery, accelerated

$0\nu\beta\beta$ Decay vs Double-Charge-Exchange Reactions

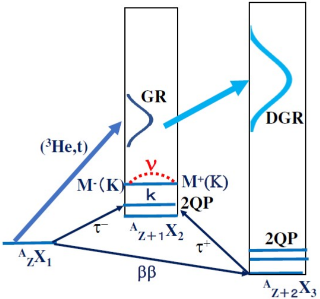
$$M^{0\nu} = M^{0\nu}_{\rm GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_{\rm F} + M^{0\nu}_{\rm T} + M^{0\nu}_{\rm S} + M^{0\nu}_{\rm N^2LO}$$

Leading contribution

$$M^{0\nu}_{\rm GT} = \langle f || \sum_{jk} \tau^-_j \tau^-_k \sigma^-_j \sigma^-_k V_{\rm GT}(r_{jk}) || i \rangle$$

- Double-Gamow-Teller (DGT) strength function

$$B({\rm DGT};\lambda) = \frac{1}{2J_i+1} |\langle f || [\sum_{jk} \sigma_j \tau^-_j \times \sigma_k \tau^-_k]^{(\lambda)} || i \rangle|^2$$



H. Ejiri, LJ, J. Suhonen, Phys. Rev. C 105, L022501 (2022)

TRIUMF

$0\nu\beta\beta$ Decay vs Double-Charge-Exchange Reactions

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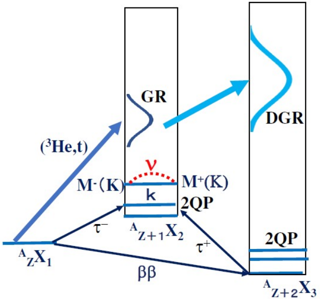
  - **Could we probe $0\nu\beta\beta$ decay by DGT reactions?**

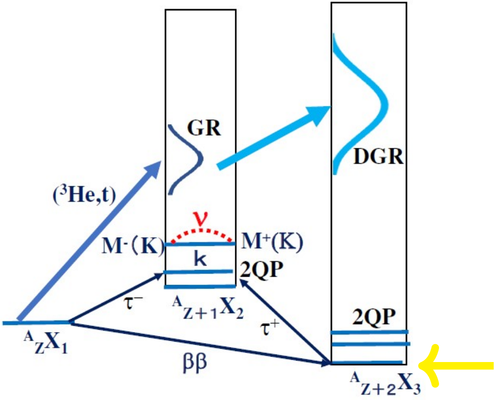


H. Ejiri, LJ, J. Suhonen, Phys. Rev. C 105, L022501 (2022)

Discovery, accelerated

Correlations Between DGT and $0\nu\beta\beta$ Decay

$$M_{\mathrm{DGT}} = -\langle 0^+_{\mathrm{gs,f}} ||[\sum_{jk} \boldsymbol{\sigma}_j \tau^-_j \times \boldsymbol{\sigma}_k \tau^-_k]^{(0)} || 0^+_{\mathrm{gs,i}} \rangle$$



H. Ejiri, LJ, J. Suhonen, Phys. Rev. C 105, L022501 (2022)

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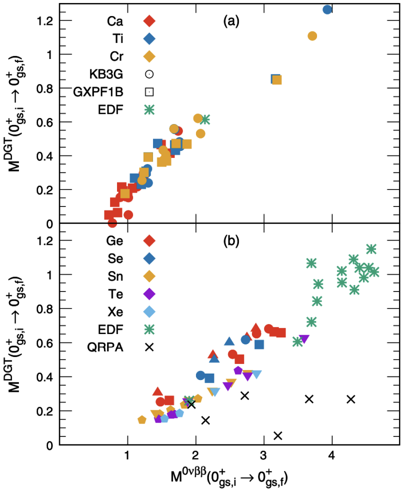
- Correlation between $M^{0\nu}$ and M_{DGT} found in **nuclear shell model** and **EFT**



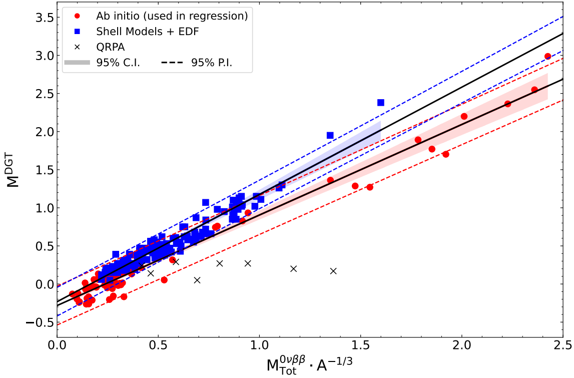
N. Shimizu, J. Menéndez, K. Yako, Phys. Rev. Lett. 120, 142502 (2018)

Discovery, accelerated

Correlations Between DGT and $0\nu\beta\beta$ Decay

$$M_{\rm DGT} = -\langle 0^+_{\rm gs,f} || [\sum_{jk} \boldsymbol{\sigma}_j \tau^-_j \times \boldsymbol{\sigma}_k \tau^-_k]^{(0)} || 0^+_{\rm gs,i} \rangle$$

- Correlation between $M^{0\nu}$ and $M_{\rm DGT}$ found in **nuclear shell model** and **EFT**
- Correlation also holds in *ab initio* **VS-IMSRG**



J. M. Yao, I. Ginnett, A. Belley et al., Phys. Rev. C 106, 014315 (2022)

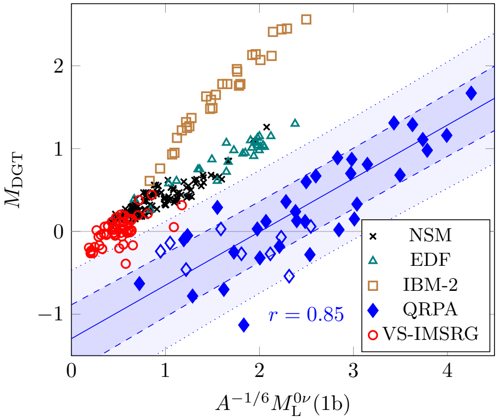
Discover accelerated

TRIUMF

Correlations Between DGT and $0\nu\beta\beta$ Decay

$$M_{\mathrm{DGT}} = -\langle 0^+_{\mathrm{gs,f}} ||[\sum_{jk} \boldsymbol{\sigma}_j \tau^-_j \times \boldsymbol{\sigma}_k \tau^-_k]^{(0)} || 0^+_{\mathrm{gs,i}} \rangle$$

- Correlation between $M^{0\nu}$ and M_{DGT} found in **nuclear shell model** and **EFT**
- Correlation also holds in *ab initio* **VS-IMSRG**
- ...and **QRPA**, when proton-neutron pairing varied
  - **Observation of M_{DGT} → constraints for $M^{0\nu}$**

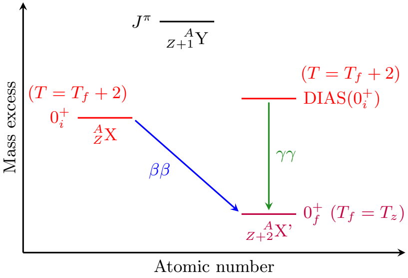


LJ, J. Menéndez, Phys. Rev. C 107, 044316 (2023)

Discovery, accelerated

Probing $0\nu\beta\beta$ Decay by Gamma Decays

- Double magnetic dipole (M1) decay (**electromagnetic interaction**) can be related to $0\nu\beta\beta$ decay (**weak interaction**)



$$M^{\gamma\gamma}(M1M1) = \sum_n \frac{(0^+_{\mathbf{f}}||\mathbf{M_1}||1^+_n)(1^+_n||\mathbf{M_1}||0^+_{\mathbf{i}})}{E_n - (E_i + E_f)/2},$$

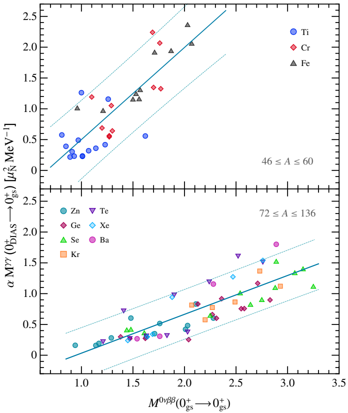
$$\mathbf{M_1} = \mu_N \sqrt{\frac{3}{4\pi}} \sum_{i=1}^{A} (g_i^l \boldsymbol{\ell}_i + g_i^s \mathbf{s}_i)$$

Discovery, accelerated

Probing $0\nu\beta\beta$ Decay by Gamma Decays

- Double magnetic dipole (M1) decay (**electromagnetic interaction**) can be related to $0\nu\beta\beta$ decay (**weak interaction**)
- Correlation between these processes observed in NSM

B. Romeo, J. Menéndez, C. Peña-Garay, Phys. Lett. B **827**, 136965 (2022)



*B. Romeo, J. Menéndez, C. Peña-Garay, Phys. Lett. B **827**, 136965 (2022)*

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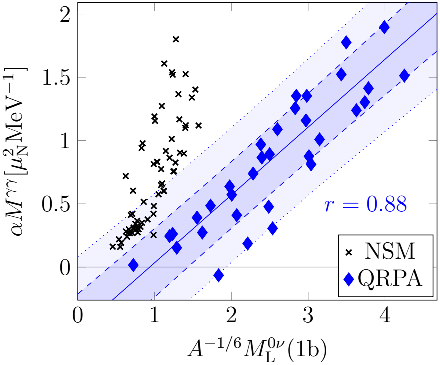
  B. Romeo, J. Menéndez, C. Peña-Garay, Phys. Lett. B **827**, 136965 (2022)
- Correlation also found in QRPA



*LJ, J. Menéndez, Phys. Rev. C **107**, 044316 (2023)*

TRIUMF

Discovery, accelerated

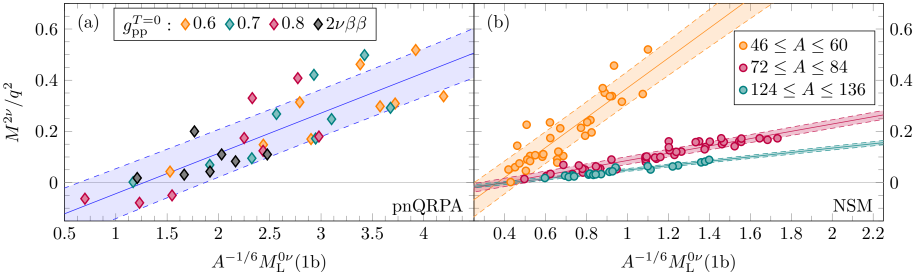
Probing $0\nu\beta\beta$ Decay by $2\nu\beta\beta$ Decay

- *How about $2\nu\beta\beta$ decay?*

Discovery, accelerated

Probing $0\nu\beta\beta$ Decay by $2\nu\beta\beta$ Decay

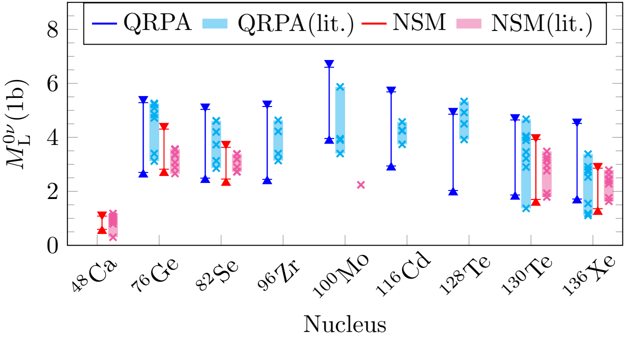
- ***How about $2\nu\beta\beta$ decay?***
- $2\nu\beta\beta$-decay also correlated with $0\nu\beta\beta$-decay!



*LJ, B. Romeo, P. Soriano and J. Menéndez, Phys. Rev. C **107**, 044305 (2023)*

Probing $0\nu\beta\beta$ Decay by $2\nu\beta\beta$ Decay

- ***How about $2\nu\beta\beta$ decay?***
- $2\nu\beta\beta$-decay also correlated with $0\nu\beta\beta$-decay!
- We can use the existing data to estimate $0\nu\beta\beta$-decay NMEs!



LJ, B. Romeo, P. Soriano and J. Menéndez, Phys. Rev. C **107**, 044305 (2023)

Outline

Discovery, accelerated

TRIUMF

Summary

- The nuclear matrix elements of $0\nu\beta\beta$ decay are sensitive to nuclear structure
- χEFT corrections to $0\nu\beta\beta$-decay seem to respect the power counting, but N^{2}LO corrections still significant
- Correlation between $0\nu\beta\beta$ and $2\nu\beta\beta$ decays helped us predict $0\nu\beta\beta$-decay NMEs with uncertainties
- Correlations with DGT and M1M1 transitions with future data can help us further constrain the NMEs

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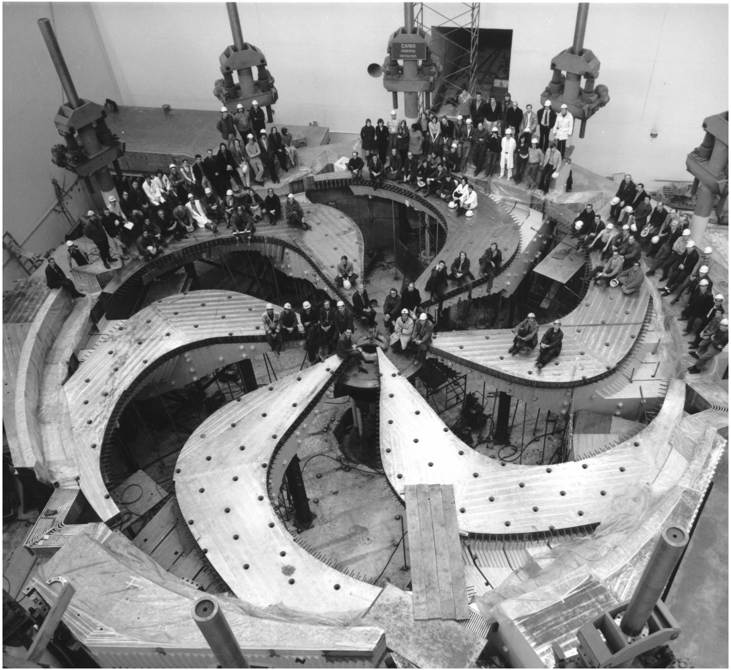
Thank you
Merci



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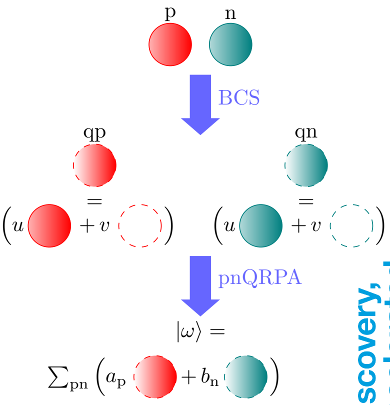
Spherical proton-neutron quasiparticle random-phase approximation (pnQRPA)

- Single-particle bases from Woods-Saxon potential



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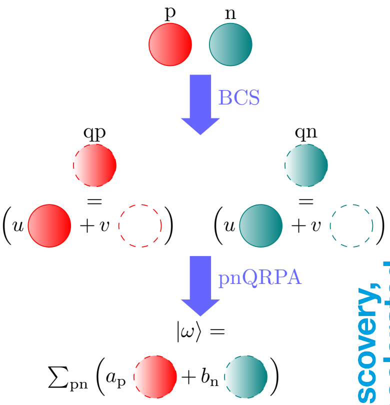

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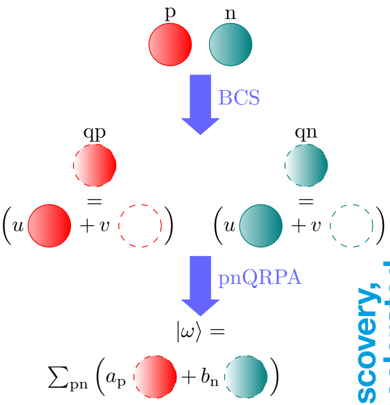

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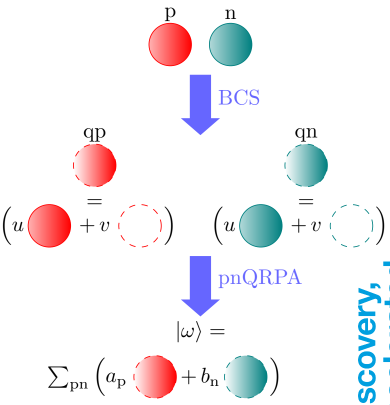
- Adjustable parameters:

$$g_{\mathrm{ph}}\,\langle p' n'^{-1}, J|\,V\,|pn^{-1}, J\rangle$$

$$g_{\mathrm{pp}}\,\langle p' n', J|\,V\,|pn, J\rangle$$

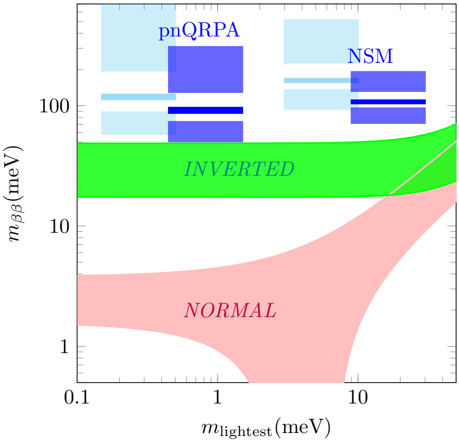


Effective Neutrino Masses

- Effective neutrino masses combining the likelihood functions of GERDA (^{76}Ge), CUORE (^{130}Te), EXO-200 (^{136}Xe) and KamLAND-Zen (^{136}Xe)

*S. D. Biller, Phys. Rev. D **104**, 012002 (2021)*

- Middle bands: $M_{\mathrm{L}}^{(0\nu)}$
  Lower bands: $M_{\mathrm{L}}^{(0\nu)} + M_{\mathrm{S}}^{(0\nu)}$
  Upper bands: $M_{\mathrm{L}}^{(0\nu)} - M_{\mathrm{S}}^{(0\nu)}$



*LJ, P. Soriano and J. Menéndez, Phys. Lett. B **823**, 136720 (2021)*

TRIUMF

Traditional nuclear matrix elements of neutrinoless double-beta decay

$$M^{0\nu} = \frac{R}{g_A^2}\int \frac{\mathrm{d}\mathbf{k}}{2\pi^2}\frac{e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})}}{E_\nu}\sum_n \frac{\langle f|\, J_\mu(\mathbf{x})\,|n\rangle\,\langle n|\,J^\mu(\mathbf{y})\,|i\rangle}{E_\nu + E_n - \frac{1}{2}(E_i+E_f) - \frac{1}{2}(E_1 - E_2)}$$

- Energy of the virtual neutrino typically $E_\nu = \sqrt{m_\nu^2 + \mathbf{k}^2} \sim |\mathbf{k}| \sim k_F \sim 100$ **MeV** ("soft neutrinos")

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TRIUMF

Closure approximation

Without closure approximation:

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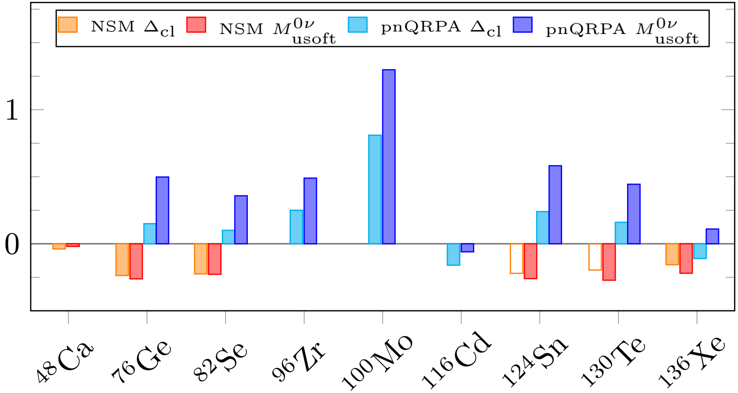
  - Typically used **with other nuclear methods**

Ultrasoft Neutrinos as Closure Correction



$$\Delta_{cl} = M^{0\nu}_{non-cl} - M^{0\nu}_{cl}$$

D. Castillo, LJ, P. Soriano, J. Menéndez, Phys. Lett. B 860, 139181 (2025)

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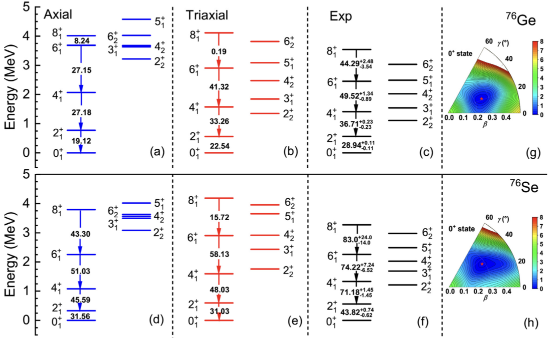
$A = 76$ Energies in ReCD



Y. Wang et al., Science Bulletin 69, 2017–2020 (2024)

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