Current status of neutrinoless $\beta\beta$ decay nuclear matrix elements

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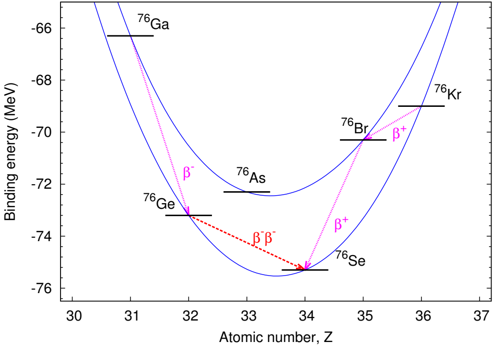
東京大学
THE UNIVERSITY OF TOKYO

科研費
KAKENHI

Neutrinoless $\beta\beta$ decay

Lepton-number violation, Majorana nature of neutrinos

Second order process only observable in rare cases
with β-decay energetically forbidden or hindered by ΔJ



Best limit: ^{76}Ge (GERDA), ^{130}Te (CUORE), ^{136}Xe (EXO, KamLAND-Zen)

Nuclear matrix elements for fundamental physics

Neutrinos, dark matter studied in experiments using nuclei

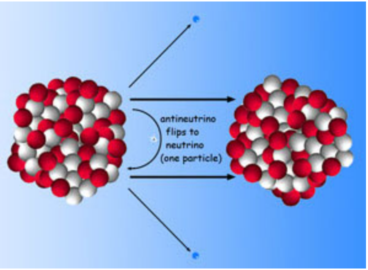
Nuclear matrix elements depend on nuclear structure crucial to anticipate reach and fully exploit experiments

$0\nu\beta\beta$ decay: $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$

Dark matter: $\dfrac{d\sigma_{\chi\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i\, \zeta_i\, \mathcal{F}_i\right|^2$

$M^{0\nu\beta\beta}$: Nuclear matrix element

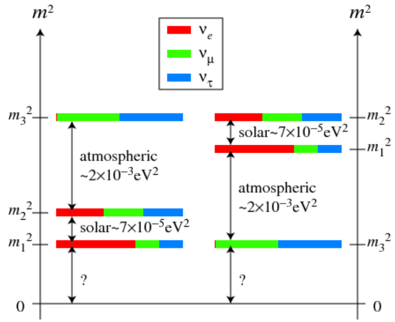
$\mathcal{F}_i$: Nuclear structure factor

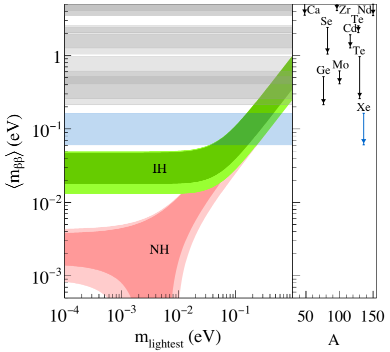


Next generation experiments: inverted hierarchy

The decay lifetime is $$T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

sensitive to absolute neutrino masses, $m_{\beta\beta} = \left|\sum U_{ek}^2 m_k\right|$, and hierarchy





KamLAND-Zen, PRL117 082503(2016)

Matrix elements needed to make sure next generation ton-scale experiments fully explore "inverted hierarchy"

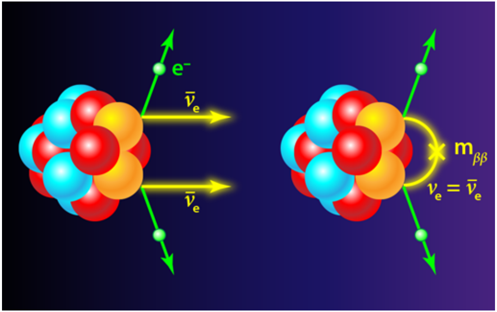
Calculating nuclear matrix elements

Nuclear matrix elements needed to study fundamental symmetries

$$\langle \text{Final} \,|\, \mathcal{L}_{\text{leptons}-\text{nucleons}} \,|\, \text{Initial} \rangle = \langle \text{Final} \,|\, \int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial} \rangle$$

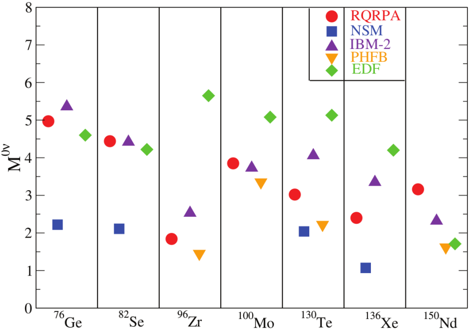
- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body methods
  GFMC, Coupled-cluster, IM-SRG...

- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD
  V. Cirigliano's talk

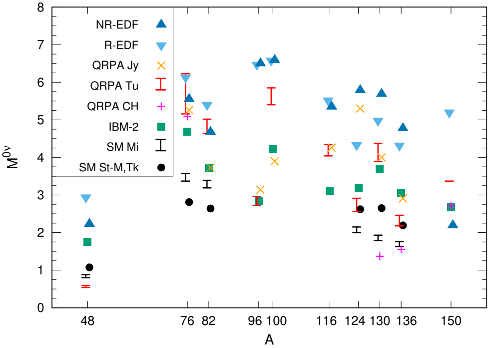


$0\nu\beta\beta$ nuclear matrix elements: last 5 years

Comparison of nuclear matrix element calculations: 2012 vs 2017



Vogel, J. Phys. G 39 124002 (2012)



Engel, JM, Rep.Prog.Phys. 80 046301(2017)

What have we learned in the last 5 years?

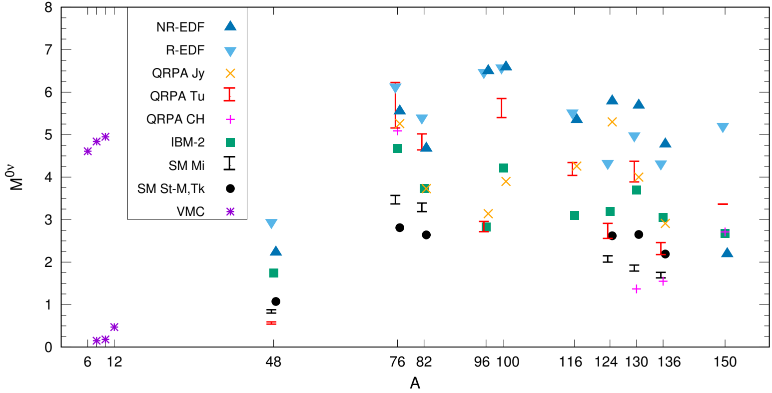
$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations: factor $\sim 2-3$

$$\langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\, \Omega^X \, |0_i^+\rangle$$

Ω^X = Fermi ($\mathbb{1}$), GT ($\sigma_n \sigma_m$),Tensor

$H(r)$ = neutrino potential

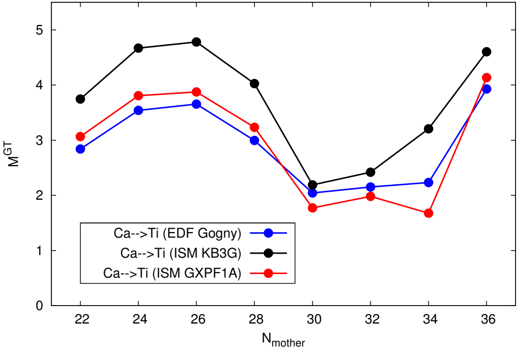


Ab initio Quantum Monte Carlo $0\nu\beta\beta$: Pastore et al. PRC97 014606(2018)

$0\nu\beta\beta$ decay without correlations

Non-realistic spherical (uncorrelated) mother and daughter nuclei:

- Shell model (SM): zero seniority, neutron and proton $J = 0$ pairs
- Energy density functional (EDF): only spherical contributions



In contrast to full (correlated) calculation SM and EDF NMEs agree!

NME scale set by pairing interaction

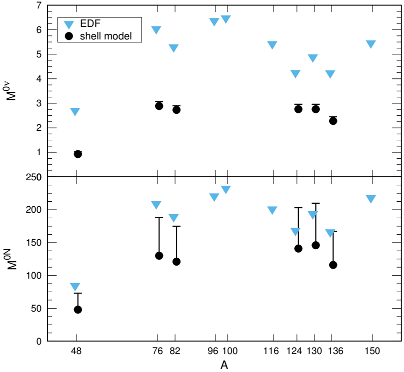
JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)

NME follows generalized seniority model:

$M_{GT}^{0\nu\beta\beta} \simeq \alpha_\pi \alpha_\nu \sqrt{N_\pi + 1}\sqrt{\Omega_\pi - N_\pi}\sqrt{N_\nu}\sqrt{\Omega_\nu - N_\nu + 1}$, Barea, Iachello PRC79 044301(2009)

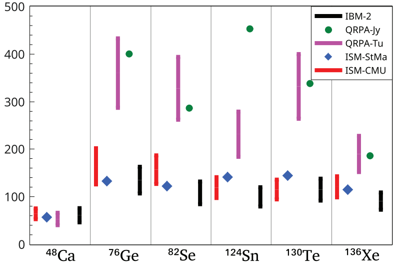
Heavy-neutrino exchange nuclear matrix elements

Contrary to light-neutrino-exchange, for heavy-neutrino-exchange decay shell model, IBM, and EDF matrix elements agree reasonably!



Song et al. PRC95 024305 (2017)

JM, JPG 45 014003 (2018)



Neacsu et al. PRC100 052503 (2015)

Longer-range nuclear correlations drive light-neutrino exchange diffs.

Heavy ν's: short-range correlations

Cruz-Torres et al. arXiv:1710:07966

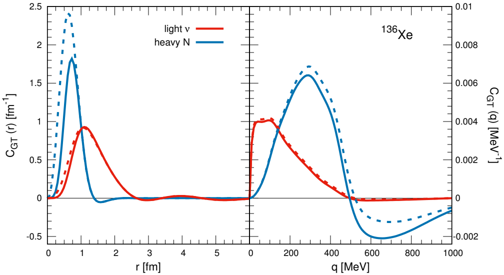
Heavy-neutrino exchange and correlations

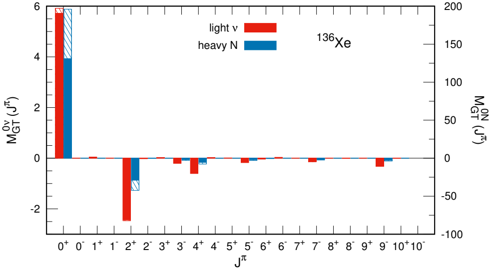
Compared to
light-neutrino exchange

heavy neutrino exchange
dominated by
shorter internucleon range,
larger momentum transfers

heavy neutrino exchange
contribution
from $J > 0$ pairs smaller:
pairing most relevant

$\Rightarrow$
Long-range correlations
(except pairing)
not under control



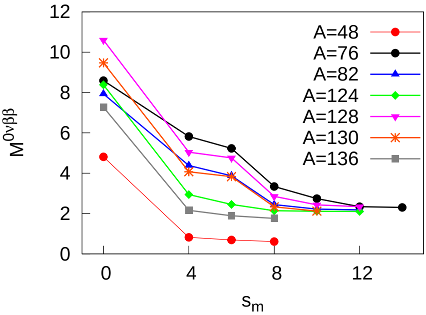


JM, JPG 45 014003 (2018)

Pairing correlations and $0\nu\beta\beta$ decay

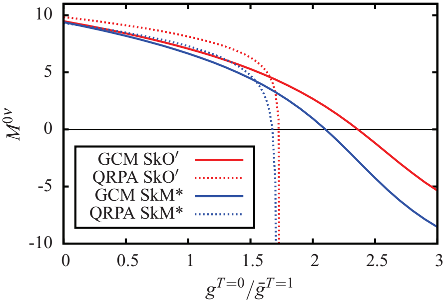
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing, but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix element value



Hinohara, Engel PRC90 031301 (2014)

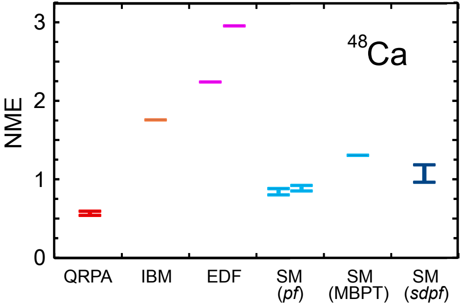
Related to approximate $SU(4)$ symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator

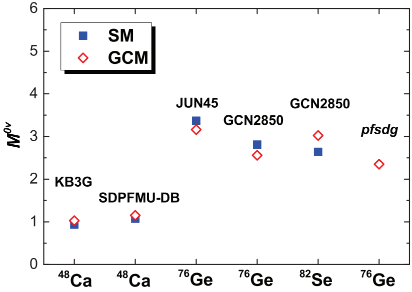
Shell model matrix elements in two shells

$^{48}Ca \rightarrow ^{48}Ti\ 0\nu\beta\beta$ decay

Enlarge configuration space from *pf* to *sdpf*, 4 to 7 orbitals

Test excitation energy of 0_2^+ in ^{48}Ca off by 1.3MeV in *pf* shell





Nuclear matrix element increases moderately 30%

Iwata et al. PRL116 112502 (2016)

Likewise, very mild effect found in GCM calculations of ^{76}Ge

Jiao et al. PRC96 054310 (2017)

Ab initio many-body methods

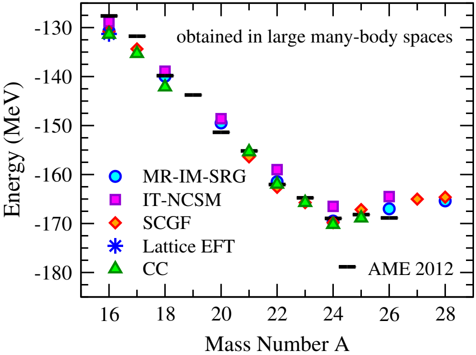
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

No-core shell model
(Importance-truncated)

In-medium SRG
Hergert et al. PRL110 242501(2013)

Self-consistent Green's function
Cipollone et al. PRL111 062501(2013)

Coupled-clusters
Jansen et al. PRL113 142502(2014)

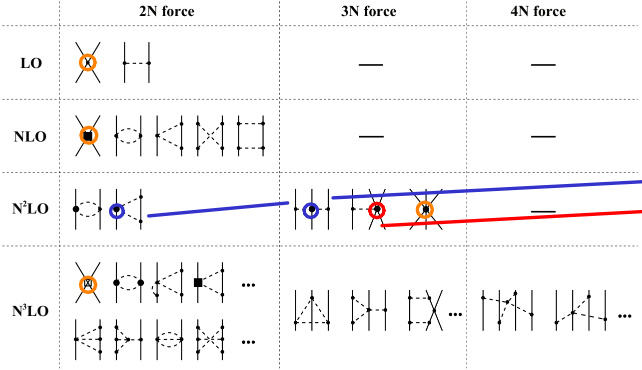


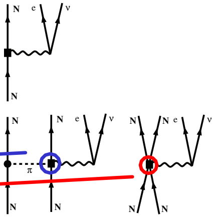
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...

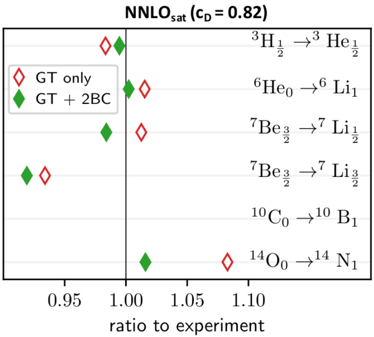
Park, Baroni, Krebs...

2b currents applied to
νd scattering (SNO),
^{3}H β-decay, μ moment...

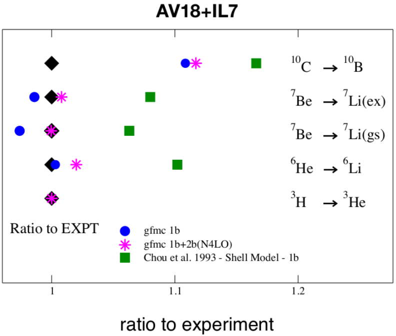
β decay in very light nuclei: GFMC vs NCSM

Quantum Monte Carlo, No Core Shell Model β decays in $A \leq 10$

Pastore et al. PRC97 022501 (2018), G. Hagen et al., INT-18-1a program



No-core shell model



Quantum Monte Carlo

Very good agreement to experiment, except ^{10}C (structure)

Impact of 2b currents small (few %), disagreement on sign

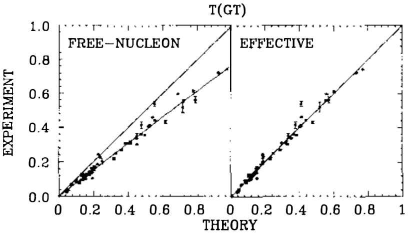
β decay in medium-mass nuclei: IMSRG

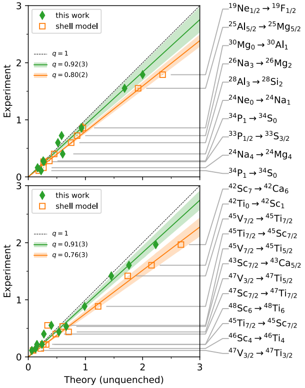
TRIUMF — "Quenching" of g_A in Gamow-Teller Decays

VS-IMSRG calculations of GT transitions in sd, pf shells

Minor effect from consistent effective operator

Significant effect from neglected 2-body currents



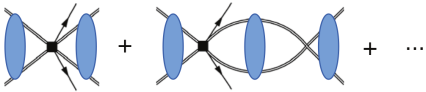


Ab initio calculations explain data with unquenched g_A

From J. Holt, INT-18-1a program

Open questions: transition operator

Contact light-neutrino operator

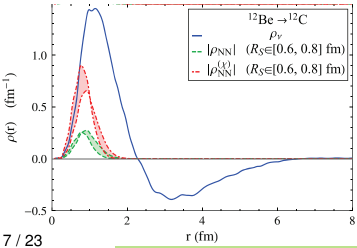


Cirigliano et al. PRL120 202001(2018)

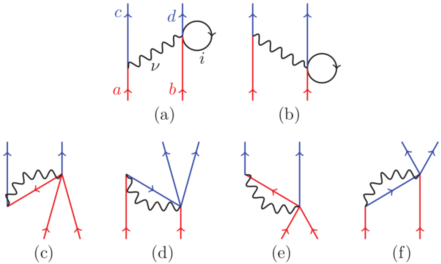
Unknown coupling value

V. Cirigliano's talk

Short-range character



Two-body currents in $\beta\beta$ decay



Estimated effect $\sim$ 10%

Wang et al. arXiv:1805:10276

compared to $\sim$ 20%
in single-β decay ("quenching")

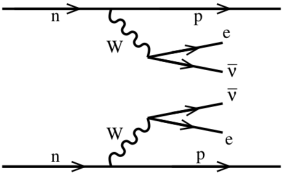
JM et al. PRL107 062501(2011)

Test of nuclear structure

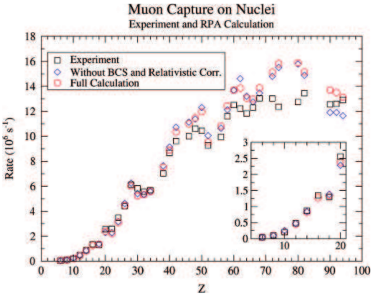
Test of $0\nu\beta\beta$ decay: comparison of predicted $2\nu\beta\beta$ decay vs data, momentum transfers $q \sim 100$ MeV: μ-capture, inelastic ν scattering

Shell model reproduce $2\nu\beta\beta$ data including "quenching" common to β decays in same mass region

Shell model prediction previous to ^{48}Ca measurement!



$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \sigma_n \tau_n^- \; |1_k^+\rangle \langle 1_k^+ | \sum_m \sigma_m \tau_m^- \; |0_i^+\rangle}{E_k - (M_i + M_f)/2}$$



μ-capture, ν-nucleus scattering
many multipoles (J values), like $0\nu\beta\beta$ decay

Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance
in double charge-exchange reactions ^{48}Ca(pp,nn)^{48}Ti proposed in 80's

Auerbach, Muto, Vogel... 1980's, 90's

Recent experimental plans in RCNP, RIKEN (^{48}Ca), INFN Catania

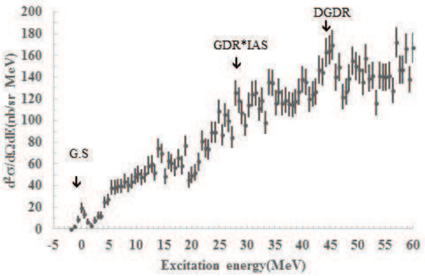
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

Capuzzello et al. EPJA 51 145 (2015), Takahisa, Ejiri et al. arXiv:1703.08264

Promising connection to $\beta\beta$ decay,
two-particle-exchange process,
especially the (tiny) transition
to ground state of final state

Two-nucleon transfers related to
$0\nu\beta\beta$ decay matrix elements

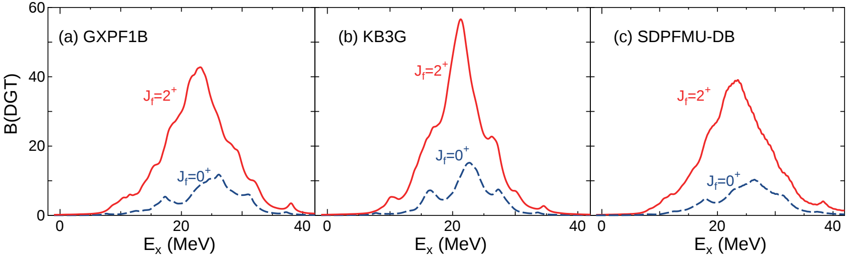
Brown et al. PRL113 262501 (2014)



^{48}Ca Double Gamow-Teller distribution

Calculate with shell model ^{48}Ca 0^{+}_{gs} Double Gamow-Teller distribution

$$B(DGT^{-};\lambda;i\to f)=\frac{1}{2J_i+1}\left|\left\langle {}^{48}\mathrm{Ti}\middle\|\left[\sum_i \boldsymbol{\sigma}_i\tau_i^{-}\times\sum_j \boldsymbol{\sigma}_j\tau_j^{-}\right]^{(\lambda)}\middle\|{}^{48}\mathrm{Ca}_{gs}\right\rangle\right|^2$$

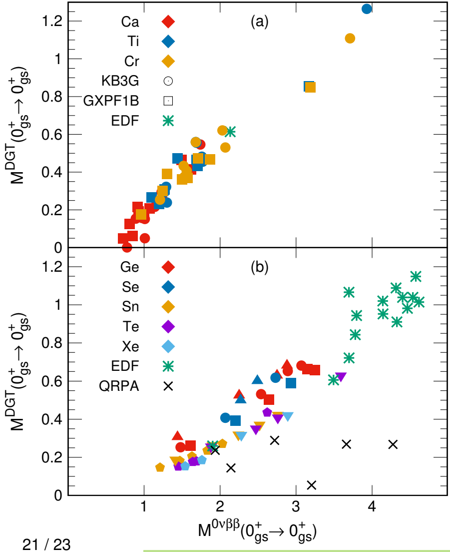


Shell model calculation with Lanczos strength function method

Double GT resonances in one and two shells rather similar result

Shimizu, JM, Yako, PRL120 142502 (2018)

DGT and $0\nu\beta\beta$ decay: heavy nuclei



DGT transition to ground state

$$M^{\mathrm{DGT}} = \sqrt{B(DGT_-; 0; 0^+_{\mathrm{gs}} \to 0^+_{\mathrm{gs}})}$$

very good linear correlation with $0\nu\beta\beta$ decay nuclear matrix elements

Correlation holds across wide range of nuclei, from Ca to Ge and Xe

Common to shell model and energy-density functional theory

$0 \lesssim M^{0\nu\beta\beta} \lesssim 5$

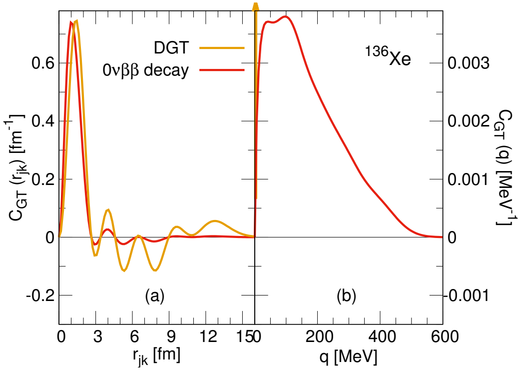
disagreement to QRPA

Shimizu, JM, Yako,
PRL120 142502 (2018)

Short-range character of DGT, $0\nu\beta\beta$ decay

Correlation between DGT and $0\nu\beta\beta$ decay matrix elements explained by transition involving low-energy states combined with dominance of short distances between exchanged/decaying neutrons

Bogner et al. PRC86 064304 (2012)



$0\nu\beta\beta$ decay matrix element limited to shorter range

Short-range part dominant in double GT matrix element due to partial cancellation of mid- and long-range parts

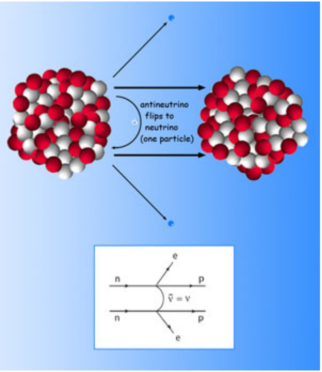
Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako,
PRL120 142502 (2018)

Summary

Nuclear matrix elements are key
for the design of next-generation tonne-scale $0\nu\beta\beta$ decay experiments
and for fully exploiting the experimental results

- Present matrix element calculations disagree
  Need improved calculations,
  guidance from other nuclear experiments
- Ab initio matrix elements in light nuclei
  ab initio matrix elements in $\beta\beta$ emitters soon!
- Double Gamow-Teller transitions
  pursued in RIKEN, INFN LNS, RCNP Osaka
  can provide very useful insight on
  value of $0\nu\beta\beta$ decay matrix elements



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