Double charge exchanges for $\beta\beta$ decays

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Center for Nuclear Study (CNS)

東京大学 THE UNIVERSITY OF TOKYO

科研費 KAKENHI

Nuclear matrix elements for fundamental physics

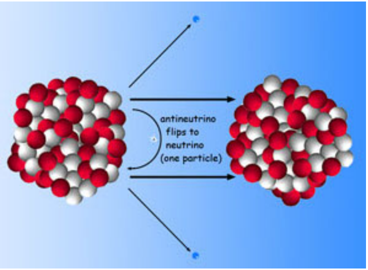
Neutrinos, dark matter studied in experiments using nuclei

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

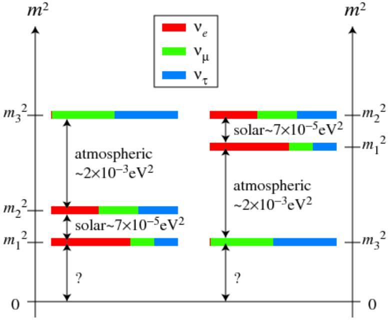
$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor

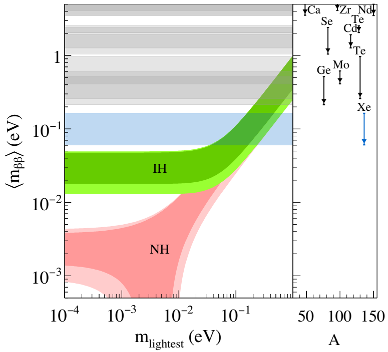


$0\nu\beta\beta$ decay experiments: inverted hierarchy

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, $m_{\beta\beta} = |\sum U_{ek}^2 m_k|$, and hierarchy





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

KamLAND-Zen, PRL117 082503(2016)

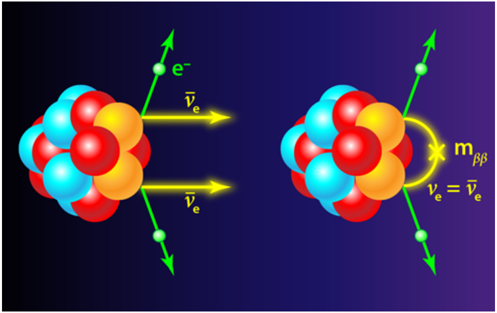
Nuclear matrix elements

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

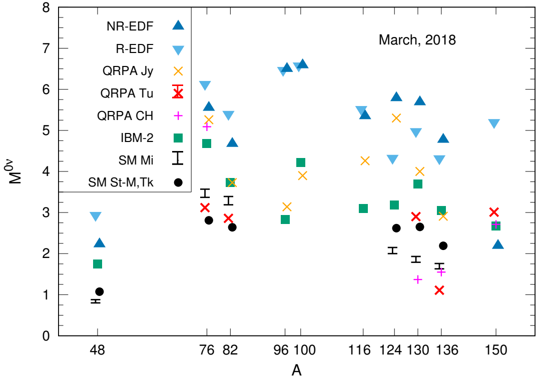


$0\nu\beta\beta$ decay nuclear matrix elements

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



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

How can nuclear matrix elements calculations improve?

How can nuclear structure experiments guide $0\nu\beta\beta$ decay?

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

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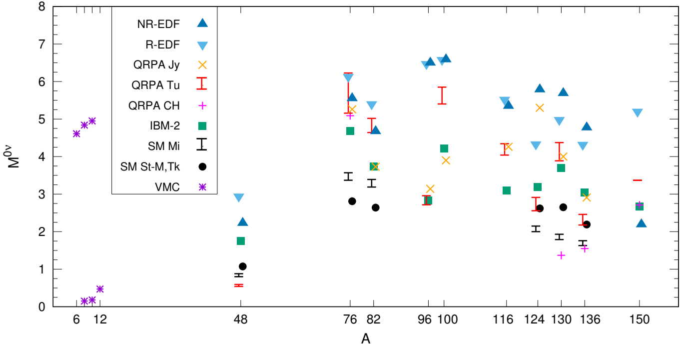
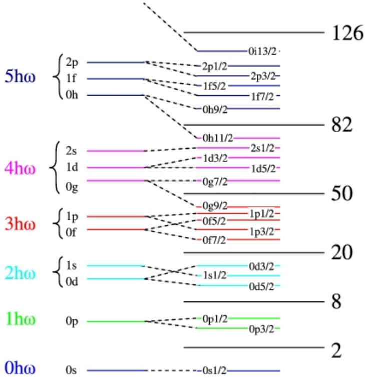


Ab initio quantum Monte Carlo $0\nu\beta\beta$: Pastore et al. PRC97 014606(2018)
Phenomenological many-body: shell model, EDF theory, QRPA, IBM...

Configuration space



Nuclear shell model configuration space only keep essential degrees of freedom

- High-energy orbits: always empty
- Configuration space: where many-body problem is solved
- Inert core: always filled

$$H\,|\Psi\rangle = E\,|\Psi\rangle \;\rightarrow H_{eff}\,|\Psi\rangle_{eff} = E\,|\Psi\rangle_{eff}$$

$$|\Psi\rangle_{eff} = \sum_{\alpha} c_\alpha\,|\phi_\alpha\rangle\,, \quad |\phi_\alpha\rangle = a^+_{i1} a^+_{i2} ... a^+_{iA}\,|0\rangle$$

Shell model codes (1 major oscillator shell) $\sim 10^{10}$ Slater dets. Caurier et al. RMP77 (2005)

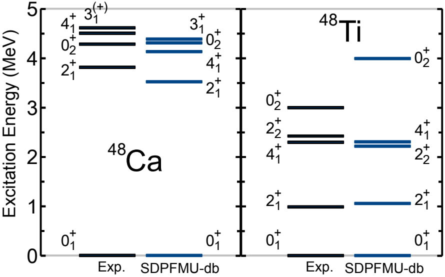
QRPA calculations suggest larger spaces ($\gtrsim$ 2 major shells) needed

Dimension $\sim$

$$\binom{(p+1)(p+2)_\nu}{N}\binom{(p+1)(p+2)_\pi}{Z}$$

Shell model configuration space: spectra

For ^{48}Ca enlarge shell model configuration space
from *pf* to *sdpf* (4 to 7 orbitals) restricted to $2\hbar\omega$ excitations
dimension of ^{48}Ti calculation increases from less than 10^6 to over 10^9



Iwata et al. PRL116 112502 (2016)

The 0_2^+ state in ^{48}Ca
is brought down by 1.3 MeV
in the *sdpf* calculation

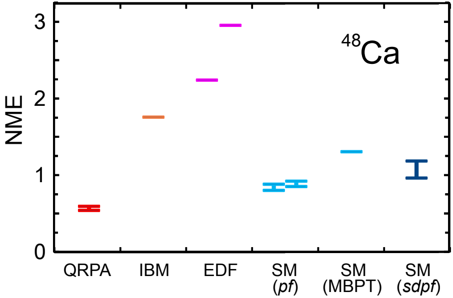
Good agreement to experiment
and with the associated
two-proton transfer cross section
($2\hbar\omega$ states dominant in ^{48}Ca 0_2^+)

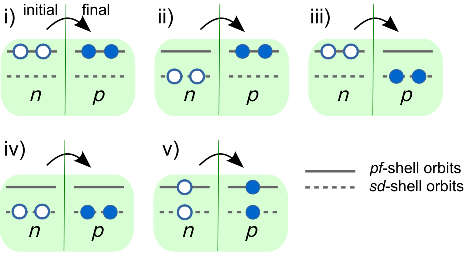
Difference in ^{48}Ca two-neutrino $\beta\beta$ decay matrix element
about 5% between *pf* and *sdpf* calculations

Shell model configuration space: two shells

For ^{48}Ca enlarge configuration space
from *pf* to *sdpf*
4 to 7 orbitals, dimension 10^5 to 10^9
increases matrix elements
but only moderately 30%

Iwata et al. PRL116 112502 (2016)



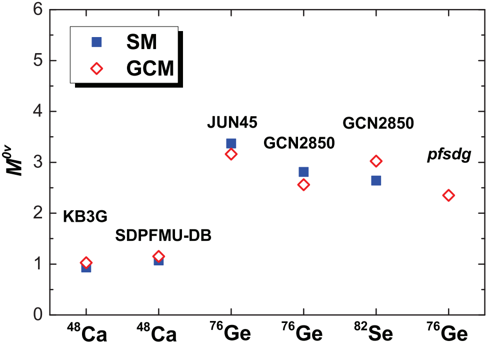


Contributions dominated by pairing
2 particle – 2 hole excitations
enhance the $\beta\beta$ matrix element,

Contributions dominated by
1 particle – 1 hole excitations
suppress the $\beta\beta$ matrix element

^{76}Ge matrix element in two shells

Large configuration space calculations in 2 major oscillator shells
Include all relevant correlations: isovector/isoscalar pairing, deformation
Many-body approach: generating coordinate method (GCM)



GCM approximates
shell model calculation

Degrees of freedom,
or generating coordinates,
validated against
exact shell model
in small configuration space

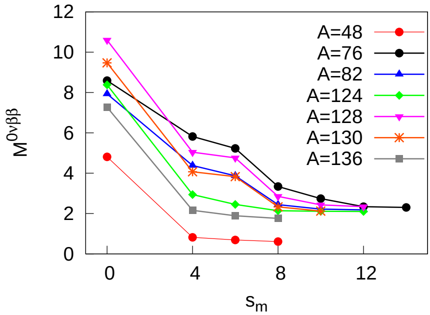
Jiao et al. PRC96 054310 (2017)

^{76}Ge nuclear matrix element in 2 major shells
very similar to shell model nuclear matrix element in 1 major shell

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

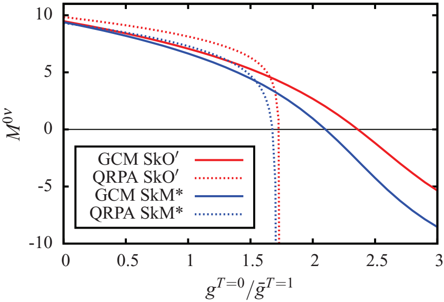
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing, but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix element value



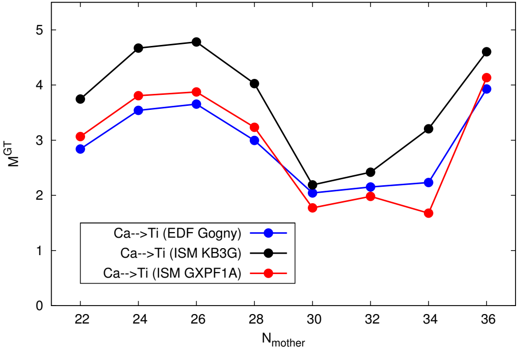
Hinohara, Engel PRC90 031301 (2014)

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

$0\nu\beta\beta$ 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

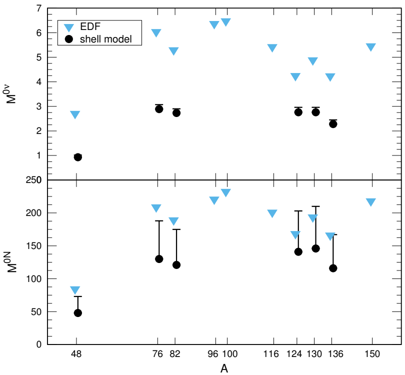
JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)

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)

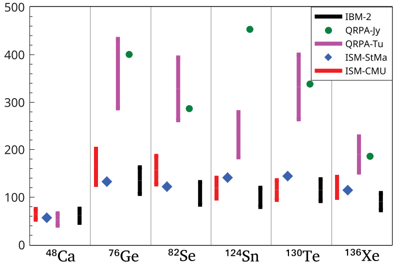
Heavy-neutrino exchange nuclear matrix elements

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)

Suggests differences in treating longer-range nuclear correlations dominant in light-neutrino exchange

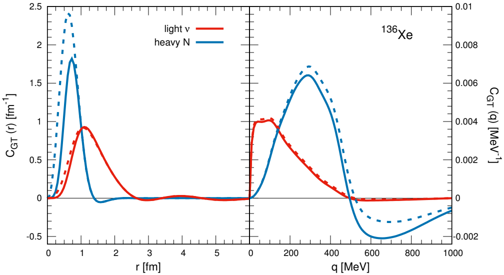
Heavy-neutrino matrix element

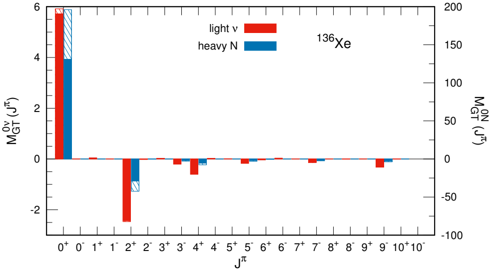
Compared to
light-neutrino exchange

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

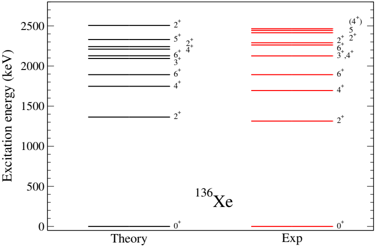


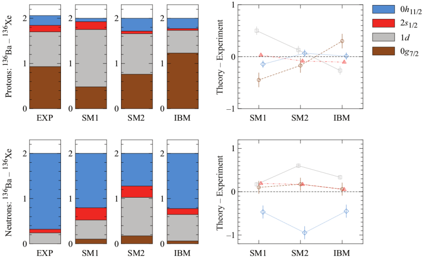


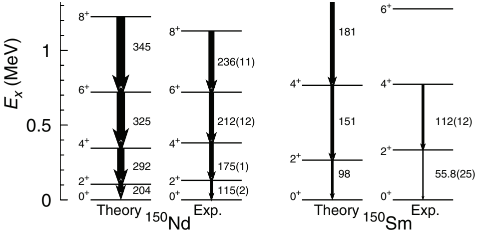
JM, JPG 45 014003 (2018)

Tests of nuclear structure

Spectroscopy well described: masses, spectra, transitions, knockout...







Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Szwec et al., PRC94 054314 (2016)

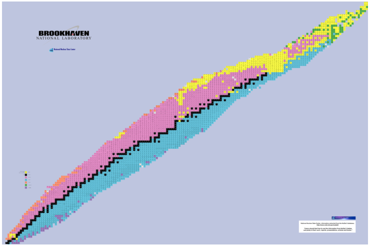
Rodríguez et al. PRL105 252503 (2010)

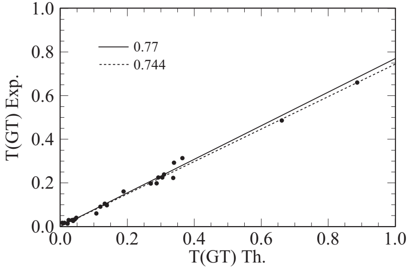
...

Vietze et al. PRD91 043520 (2015)

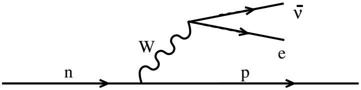
β decays

β decays (e^- capture) main decay model along nuclear chart
In general well described by nuclear structure theory: shell model...





Martinez-Pinedo et al. PRC53 2602(1996)



$$\langle F | \sum_i [g_A \, \boldsymbol{\sigma}_i \tau_i^-]^{\text{eff}} \, | I \rangle \,, \quad [\boldsymbol{\sigma}_i \tau]^{\text{eff}} \approx 0.7 \boldsymbol{\sigma}_i \tau$$

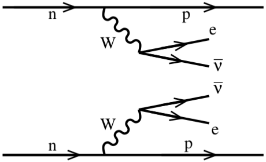
Gamow-Teller transitions:
theory needs $\boldsymbol{\sigma}_i \tau$ "quenching"

Two-neutrino $\beta\beta$ decay, μ capture, ν scattering

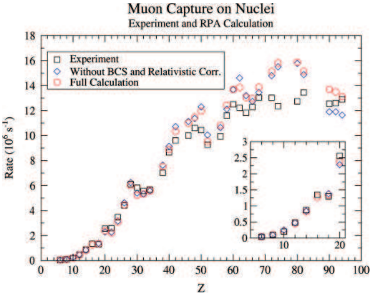
Test of $0\nu\beta\beta$ decay: comparison of predicted $2\nu\beta\beta$ decay vs data, momentum transfers $q \sim 100$ MeV: μ-capture, inelastic ν scattering

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!



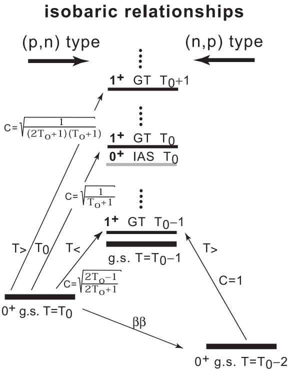
$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \sigma_n \tau_n^- | 1_k^+ \rangle \langle 1_k^+ | \sum_m \sigma_m \tau_m^- | 0_i^+ \rangle}{E_k - (M_i + M_f)/2}$$



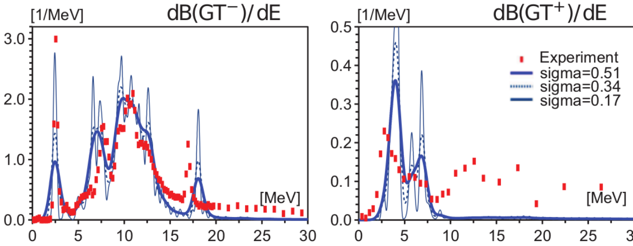
μ-capture, ν-nucleus scattering many multipoles (J values), like $0\nu\beta\beta$ decay

Gamow-Teller strength distributions

Gamow-Teller strength distributions well described by theory (quenched)



Freckers et al.
NPA916 219 (2013)



Iwata et al. JPSCP 6 03057 (2015)

$$\frac{d\sigma}{d\Omega}(\theta=0) \propto \sum_i \boldsymbol{\sigma}_i \tau^{\pm}$$

$$\langle 1_f^+ | \sum_i g_A^{\text{eff}}\, \boldsymbol{\sigma}_i \tau_i^{\pm} | 0_{gs}^+ \rangle\,, \quad g_A^{\text{eff}} \approx 0.7 g_A$$

GT strengths combined related to $2\nu\beta\beta$ decay, relative phase unknown

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)

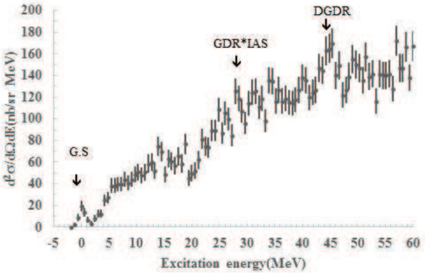
Capuzzello et al. EPJA 51 145 (2015), Takahisa, Ejiri et al. arXiv:1703.08264

Talks by Uesaka, Cappuzzello

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

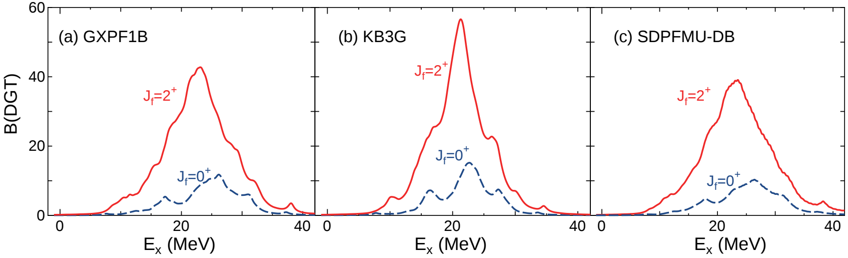
Brown et al. PRL113 262501 (2014)



^{48}Ca Double Gamow-Teller distribution

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

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



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)

Double Gamow-Teller distribution and pairing

Study the sensitivity of Double GT distribution to pairing correlations

Add/remove pairing

$$H' = H + G^{JT} P^{JT}$$

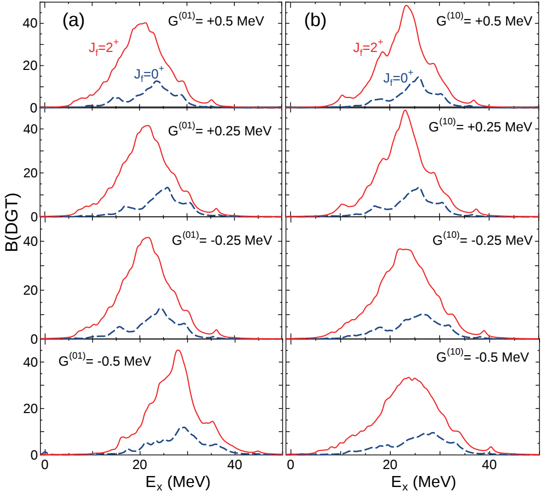
like-particle (T=1) or proton-neutron (T=0)

Position of the DGT giant resonance very sensitive to like-particle pairing

DGT resonance width probes isoscalar pairing

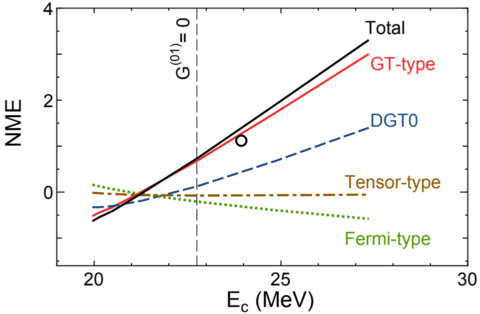
Shimizu, JM, Yako

PRL120 142502 (2018)



^{48}Ca double GT giant resonance and $0\nu\beta\beta$ decay

Correlation between Double Gamow-Teller resonance in ^{48}Ca and $0\nu\beta\beta$ decay nuclear matrix element



Energy of DGT resonance with accuracy to $\sim$1MeV, can give insight on value of $0\nu\beta\beta$ decay matrix element

$$E_{\rm av} = \frac{\sum_f E_f B(DGT^-, i \to f)}{\sum_f B(DGT^-, i \to f)}$$

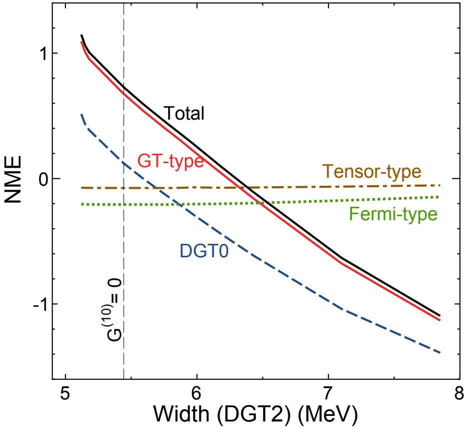
Good test of nuclear structure calculation

Shimizu, JM, Yako, PRL120 142502 (2018)

Relatively consistent with *sdpf* calculation (open circle)

^{48}Ca double GT resonance width and $0\nu\beta\beta$ decay

Correlation between the width of the double GT giant resonance and the $0\nu\beta\beta$ decay nuclear matrix element



Double GT resonance width probably not very useful to determine $0\nu\beta\beta$ matrix element

Large experimental precision much better than 1 MeV needed

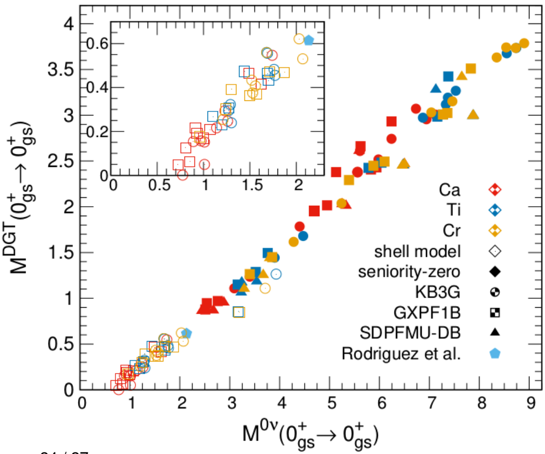
Nuclear matrix element changes sign (not observable)

$$\sigma_{DGT} = \sqrt{\frac{\sum_f (E_f - E_{\rm av})^2 B({\rm DGT}^-, i \to f)}{\sum_f B({\rm DGT}^-, i \to f)}}$$

DGT to ground state and $0\nu\beta\beta$ decay

DGT transition to ground state of final nucleus:
Ca, Ti, Cr isotopic chains

$$M^{\mathrm{DGT}} = \langle \mathrm{Final}_{gs} || \left[\sum_i \boldsymbol{\sigma}_i \tau_i^- \times \sum_j \boldsymbol{\sigma}_j \tau_j^- \right]^0 || \mathrm{Initial}_{gs} \rangle|^2$$

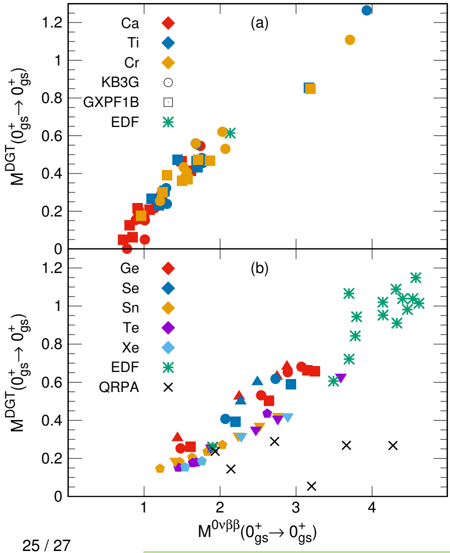


Very good linear correlation between DGT and $0\nu\beta\beta$ decay nuclear matrix elements

Linear correlation holds for $\sim$ 25 transitions studied for simplified wf's (seniority-zero), for different interactions

Shimizu, JM, Yako,
PRL120 142502 (2018)

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



DGT transition to ground state

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

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

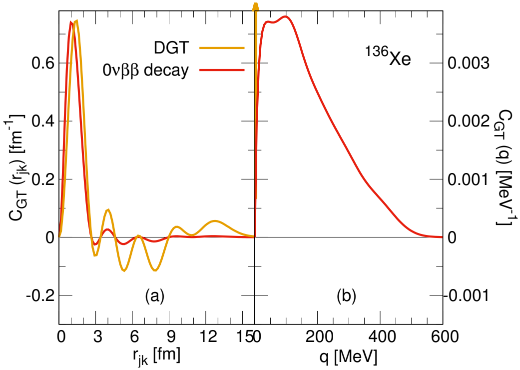
Common to shell model and energy-density functional theory $0 \lesssim M^{0\nu\beta\beta} \lesssim 5$ disagreement to QRPA

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

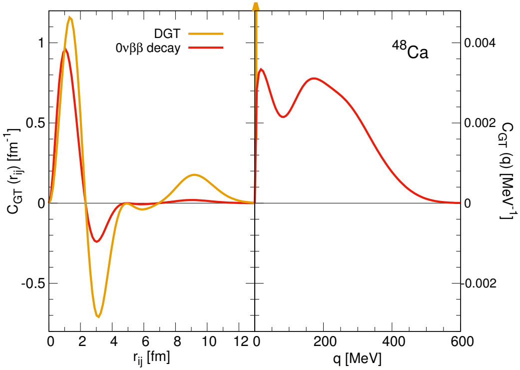
Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako,
PRL120 142502 (2018)

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

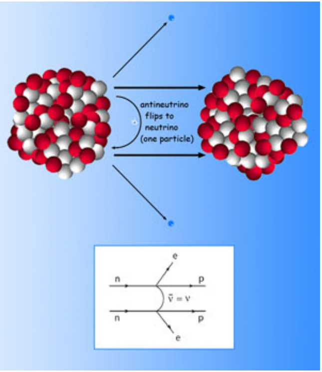
Long-range part dominant in QRPA DGT matrix elements

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
- Shell model nuclear matrix elements
  in two shells for ^{48}Ca, ^{76}Ge,
  suggest moderate enhancement ($\lesssim 30\%$)
- 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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