Test and correlations of calculated neutrinoless $\beta\beta$ decay nuclear matrix elements

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INT program
"New physics searches at the precision frontier"

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TECHNISCHE UNIVERSITÄT DARMSTADT — **C. Brase**, A. Schwenk

Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

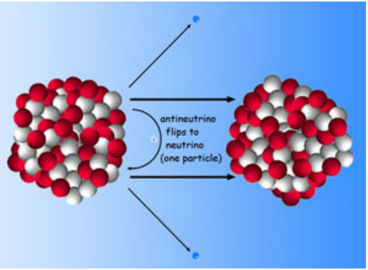
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

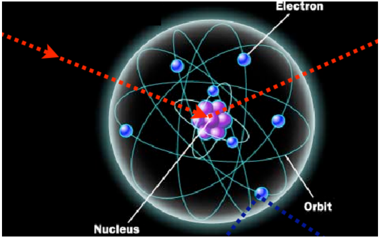
$$0\nu\beta\beta\text{:}\ \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

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

$$\text{CE}\nu\text{NS:}\ \frac{d\sigma_{\nu\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$$

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





Creation of matter in nuclei: $0\nu\beta\beta$ decay

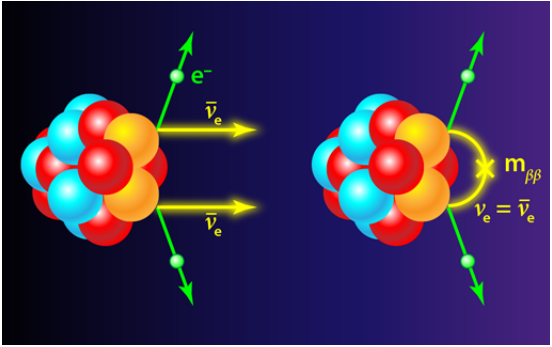
Lepton number is conserved in all processes observed:

single β decay,
$\beta\beta$ decay with neutrino emission...

Uncharged massive particles like Majorana neutrinos (ν) allow lepton number violation:

neutrinoless $\beta\beta$ decay
two matter particles (electrons) created

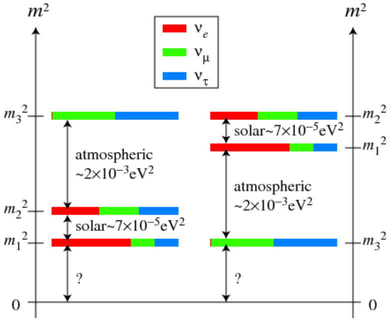
Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. in press, arXiv:2202.01787

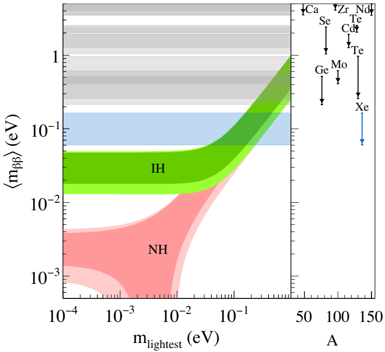


Next generation experiments: inverted hierarchy

Decay rate sensitive to
neutrino masses, hierarchy
$m_{\beta\beta} = |\sum U_{ek}^2 m_k|$

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

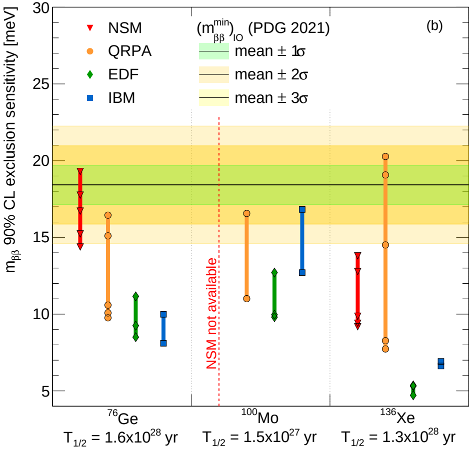




KamLAND-Zen, PRL117 082503(2016)

Matrix elements assess if
next generation experiments
fully explore "inverted hierarchy"

Uncertainty in physics reach of $0\nu\beta\beta$ experiments



Agostini, Benato, Detwiler, JM, Vissani
Phys. Rev. C 104 L042501 (2021)

Nuclear matrix element theoretical uncertainty critical to anticipate $m_{\beta\beta}$ sensitivity of future experiments

Current uncertainty in $m_{\beta\beta}$ prevents to foresee if next-generation experiments will fully cover parameter space of "inverted" neutrino mass hierarchy

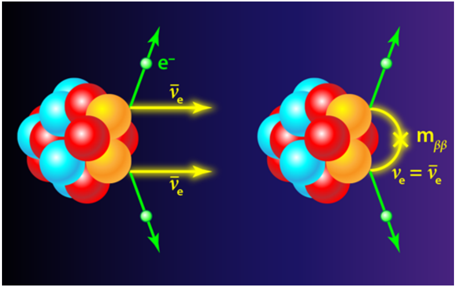
Uncertainty needs to be reduced!

Nuclear matrix elements

Nuclear matrix elements needed in low-energy new-physics searches

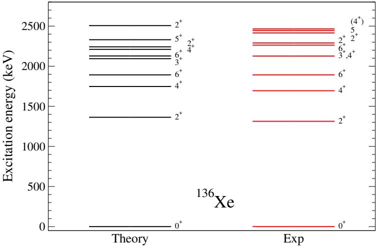
$$\langle \text{Final} \,|\mathcal{L}_{\text{leptons}-\text{nucleons}}|\, \text{Initial} \rangle = \langle \text{Final} \,|\int dx\, j^{\mu}(x) J_{\mu}(x)\,|\, \text{Initial} \rangle$$

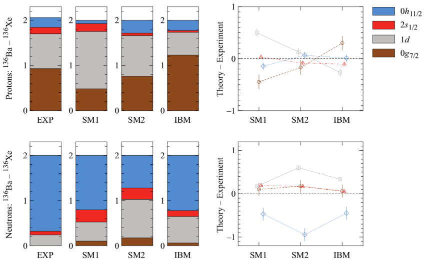
- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  QMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD



Tests of nuclear structure

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



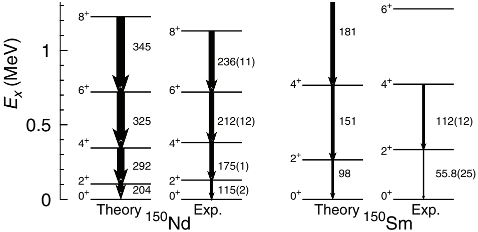


Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Szwec et al., PRC94 054314 (2016)



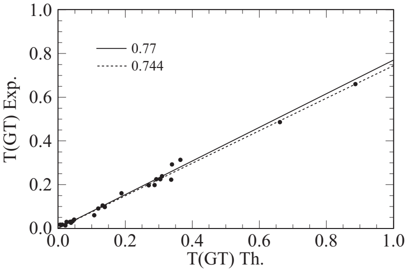
Rodríguez et al. PRL105 252503 (2010)

...

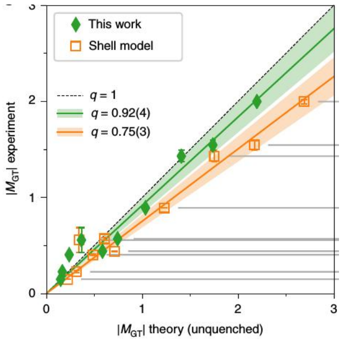
Vietze et al. PRD91 043520 (2015)

β–decay Gamow-Teller transitions: “quenching”

β decays (e^- capture): phenomenology vs ab initio



Martinez-Pinedo et al. PRC53 2602(1996)



Gysbers et al. Nature Phys. 15 428 (2019)

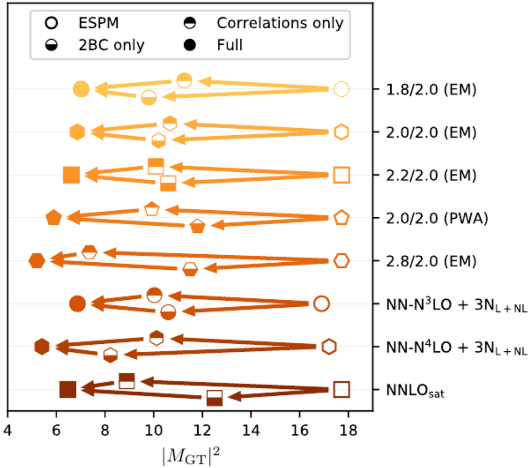
$$\langle F| \sum_i [g_A\, \boldsymbol{\sigma}_i \tau_i^-]^{\text{eff}}\, |I\rangle\,, \quad [\boldsymbol{\sigma}_i\tau]^{\text{eff}} \approx 0.7\boldsymbol{\sigma}_i\tau$$

Standard shell model needs $\boldsymbol{\sigma}_i\tau$ “quenching”

Ab initio calculations including meson-exchange currents and additional nuclear correlations do not need any “quenching”

Origin of β decay "quenching"

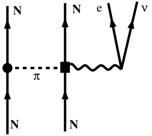
Which are main effects missing in conventional β-decay calculations?
Test case: GT decay of ^{100}Sn



Relatively similar and complementary impact of

- nuclear correlations
- meson-exchange currents

Gysbers et al.
Nature Phys. 15 428 (2019)

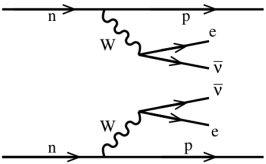


Two-neutrino $\beta\beta$ decay, 2νECEC

$2\nu\beta\beta$ decay same initial, final states , similar operator ($\sigma\tau$) as $0\nu\beta\beta$
Comparison of predicted $2\nu\beta\beta$ decay vs data

Shell model reproduce $2\nu\beta\beta$ data including "quenching"

Prediction previous to ^{48}Ca measurement!
Caurier, Poves, Zuker
PLB 252 13(1990)



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

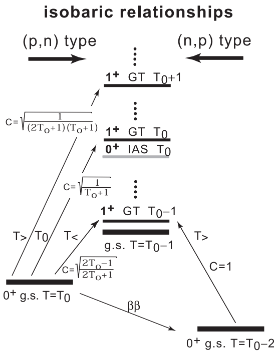
Table 2
The ISM predictions for the matrix element of several 2ν double beta decays (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
$^{48}Ca \rightarrow {}^{48}Ti$	0.047 ± 0.003	0.74	0.047	kb3
$^{48}Ca \rightarrow {}^{48}Ti$	0.047 ± 0.003	0.74	0.048	kb3g
$^{48}Ca \rightarrow {}^{48}Ti$	0.047 ± 0.003	0.74	0.065	gxpf1
$^{76}Ge \rightarrow {}^{76}Se$	0.140 ± 0.005	0.60	0.116	gcn28:50
$^{76}Ge \rightarrow {}^{76}Se$	0.140 ± 0.005	0.60	0.120	jun45
$^{82}Se \rightarrow {}^{82}Kr$	0.098 ± 0.004	0.60	0.126	gcn28:50
$^{82}Se \rightarrow {}^{82}Kr$	0.098 ± 0.004	0.60	0.124	jun45
$^{128}Te \rightarrow {}^{128}Xe$	0.049 ± 0.006	0.57	0.059	gcn50:82
$^{130}Te \rightarrow {}^{130}Xe$	0.034 ± 0.003	0.57	0.043	gcn50:82
$^{136}Xe \rightarrow {}^{136}Ba$	0.019 ± 0.002	0.45	0.025	gcn50:82

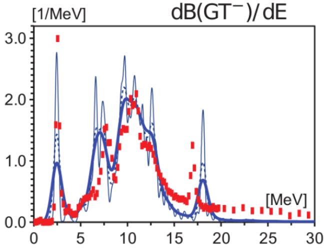
Caurier, Nowacki, Poves, PLB 711 62 (2012)

Fix “quenching” in phenomenological calculations

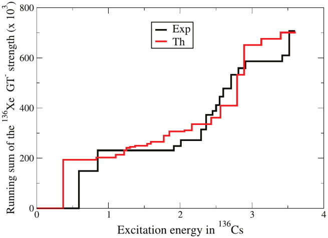
GT strength distribution complements β-decay beyond Q-value region



Frekers et al.
NPA916 219 (2013)



Iwata et al. JPSCP 6 03057 (2015)



Caurier et al. PLB 711 62 (2012)

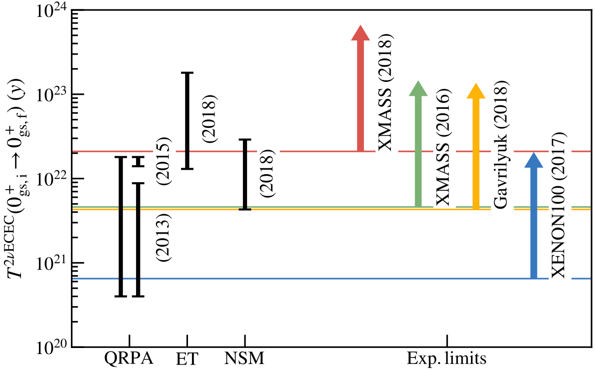
$$\frac{d\sigma}{d\Omega}(\theta=0) \propto \sum_i \boldsymbol{\sigma}_i \tau^{\pm}$$

$$\langle 1^+_f | \sum_i g_A^{\text{eff}}\, \boldsymbol{\sigma}_i \tau_i^{\pm} | 0^+_{gs} \rangle\,, \quad g_A^{\text{eff}} \sim 0.57 g_A \text{ for } {}^{136}\text{Xe}$$

Similar “quenching” q= 0.57 needed in GT decays in xenon mass region
Smaller “quenching” q= 0.42 needed in $2\nu\beta\beta$ of ^{136}Xe

Two-neutrino ECEC of ^{124}Xe

Predicted 2νECEC half-life:
shell model error bar largely dominated by "quenching" uncertainty



Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

Coello Pérez, JM, Schwenk
PLB 797 134885 (2019)

Shell model, QRPA and Effective theory (ET) predictions
suggest experimental detection close to XMASS 2018 limit

Two-neutrino ECEC of ^{124}Xe

Predicted 2νECEC half-life:
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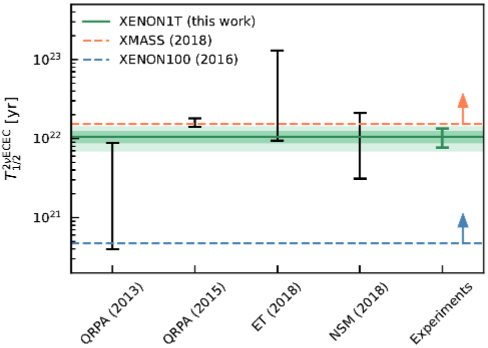


Suhonen
JPG 40 075102 (2013)

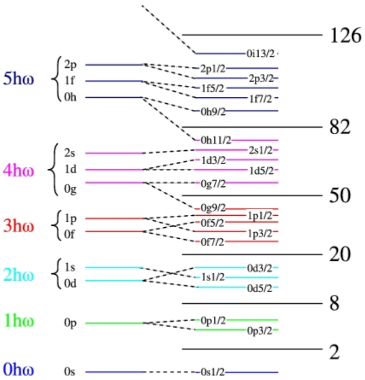
Pirinen, Suhonen
PRC 91, 054309 (2015)

Coello Pérez, JM, Schwenk
PLB 797 134885 (2019)

XENON1T
Nature 568 532 (2019)
PRC106, 024328 (2022)

Shell model, QRPA and Effective theory (ET) predictions
good agreement with XENON1T measurement of 2νECEC!

Nuclear shell model



Nuclear shell model configuration space only keep essential degrees of freedom

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

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

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

Shell model diagonalization:

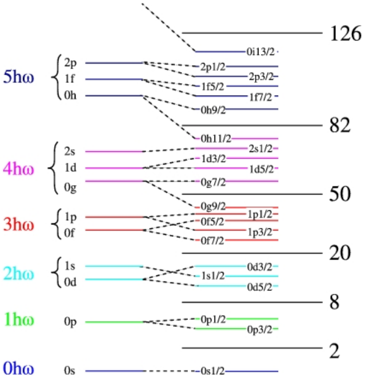
$\sim 10^{10}$ Slater dets. Caurier et al. RMP77 (2005)

$\gtrsim 10^{24}$ Slater dets. with Monte Carlo SM
Otsuka, Shimizu, Y.Tsunoda
Phys. Scr. 92 063001 (2017)

H_{eff} includes effects of

- inert core
- high-energy orbitals

QRPA method



QRPA configuration space comprises 18–25 single-particle orbitals with no core in the calculation

Intermediate states in odd-odd nuclei described as proton-neutron quasiparticles from ground states of initial and final nuclei

More limited nuclear correlations than nuclear shell model

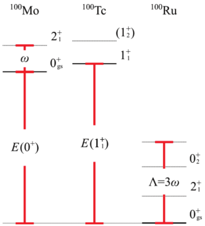
Some adjustable parameters:
especially particle-particle channel g_{pp} (isoscalar pairing) critical for a good description of $\beta\beta$ decays

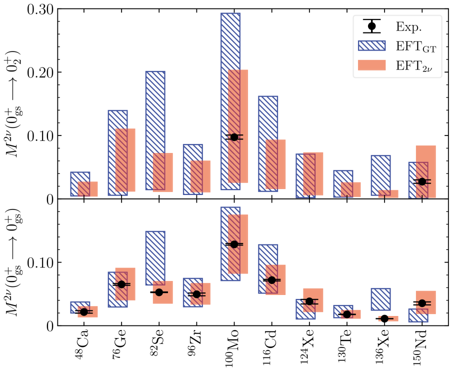
Vogel, Zirnbauer, PRL 57, 3148 (1986), Engel, Vogel, Zirnbauer, PRC 37 3148 (1988)

Effective theory of $\beta\beta$ decay

Effective theory (ET) for $\beta\beta$ decay:
spherical core coupled to one nucleon

Couplings adjusted to experimental data,
uncertainty given by effective theory
(breakdown scale, systematic expansion)





Use β-decay data
to predict $2\nu\beta\beta$ decay

Coello-Pérez, JM, Schwenk
PRC 98, 045501 (2018)

Use $2\nu\beta\beta$-decay data
predict $2\nu\beta\beta$ to excited states

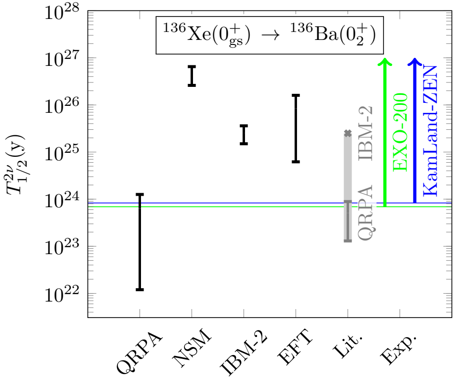
Jokiniemi, Romeo, Brase, Kotila et al.
PLB 838 137689 (2023)

Good agreement, large error
(leading-order in ET)

$2\nu\beta\beta$ decay of ^{136}Xe to ^{136}Ba 0_2^+

Current experiments sensitive to two-neutrino $\beta\beta$ of ^{136}Xe to ^{136}Ba 0_2^+

EXO-200, KamLAND-Zen



Nuclear shell model
QRPA, EFT and IBM
very different predictions!

Barea et al.
PRC 91 034304 (2015)

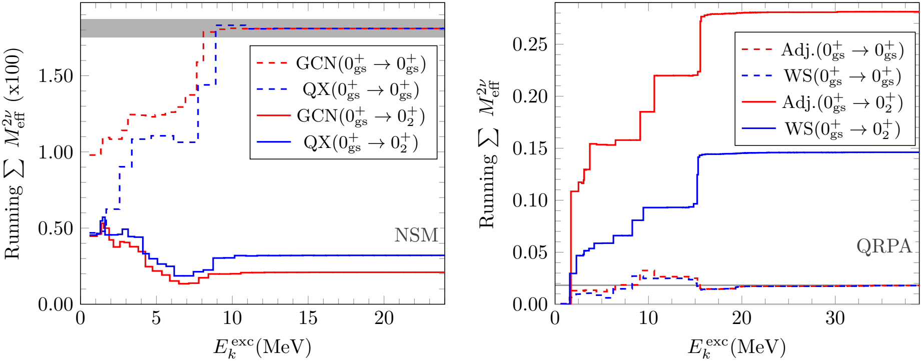
Pirinen, Suhonen
PRC 91, 054309 (2015)

Jokiniemi, Romeo, Brase, Kotila et al.
PLB 838 137689 (2023)

Very good test of theoretical calculations!

^{136}Xe $\longrightarrow$ ^{136}Ba 0_2^+ running sums

Subtle cancellation NME running sum, depends on many-body method



Jokiniemi, Romeo, Brase, Kotila et al. PLB 838 137689 (2023)

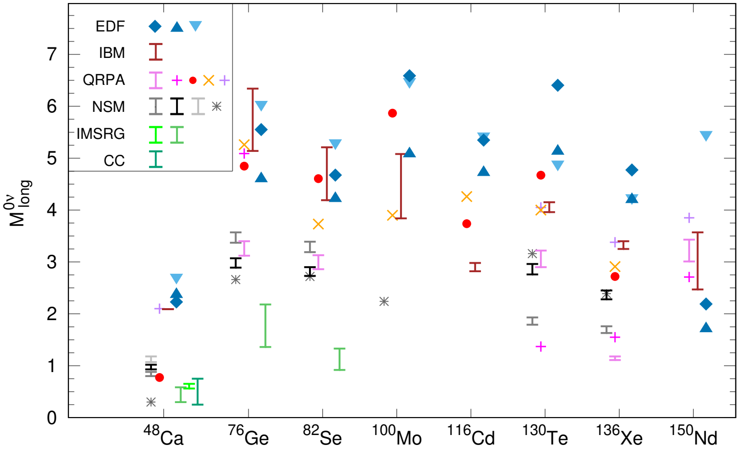
Shell-model running sum shows cancellations in decay to ground state

QRPA running sum shows cancellations in decay to excited state

Since ground-state decay fitted to data, very different decay to excited state

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

Large difference in nuclear matrix element calculations: factor ~ 3



Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. in press, arXiv:2202.01787

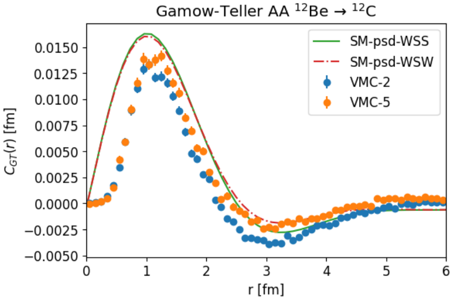
Shell model vs quantum Monte Carlo: correlations

Compare $\beta\beta$ transition densities in
nuclear shell model and quantum Monte Carlo calculations in light nuclei

$$4\pi r^2 \rho_{GT}(r) = \langle \Psi_f | \sum_{a<b} \delta(r - r_{ab}) \sigma_{ab} \tau_a^+ \tau_b^+ | \Psi_i \rangle ,$$

$$M_{GT}^{0\nu} = \int_0^\infty dr\, C_{GT}^{0\nu} ,$$

Agreement at long distances, missing short-range correlations in shell model



Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

Similar findings in Wang et al. PLB 798 134974 (2019)

Generalized contact formalism (GCF)

Generalized contact formalism Weiss, Bazak, Barnea PRL 114 012501 (2015)

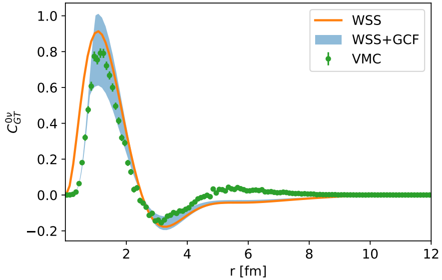
Separation of scales: wf, transition density factorize for two nearby nucleons

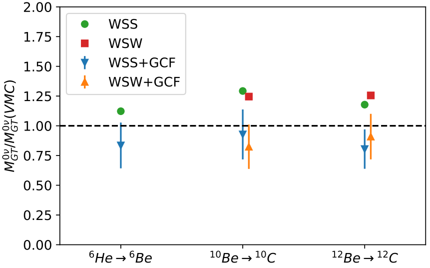
$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_\alpha \varphi^\alpha(\boldsymbol{r}_{ij}) A^\alpha(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j}), \quad \rho_{GT}(r) \xrightarrow[r\to 0]{} -3|\varphi^0(r)|^2 C^0_{pp,nn}(f,i)$$

with $\varphi(r)$ the solution of the two-nucleon Schrödinger equation

The contact $C^0(f,i) = \frac{A(A-1)}{2} \langle A^\alpha(f)|A^\beta(i)\rangle$ is model dependent

Replace shell-model by QMC contact
to improve transition density and nuclear matrix element

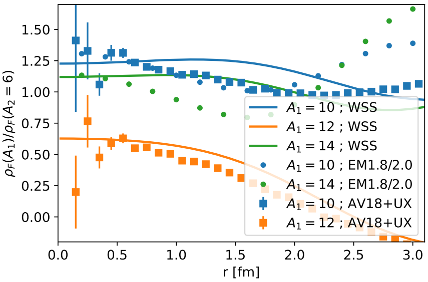


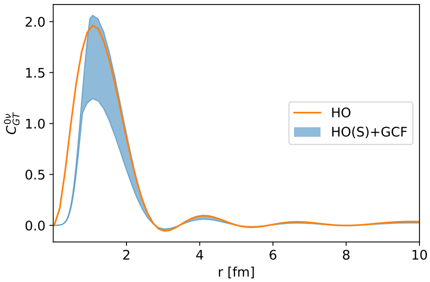


GCF: model independence of ratios

Generalized contact formalism Weiss, Bazak, Barnea PRL 114 012501 (2015)

The contact $C^0(f,i) = \frac{A(A-1)}{2}\langle A^\alpha(f)|A^\beta(i)\rangle$ is model dependent
(shell model, quantum Monte Carlo, no-core shell model...)
but for two nuclei the ratio $C^0_{pp,nn}(X)/C^0_{pp,nn}(Y)$ relatively model independent:
combine QMC calculation in light nuclei with two shell model calculations:



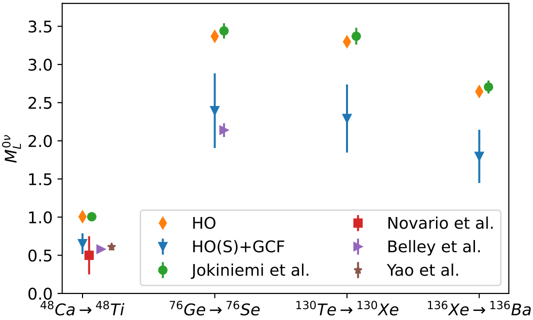


Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)
Yao, Belley et al. PRC 103, 014315 (2021)

Shell model + Generalized contact formalism: NMEs

GCF builds QMC short-range correlations to shell model transitions densities can be extended to heavy nuclei where shell model calculations are possible

Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)



Short-range correlations included by GCF reduce $0\nu\beta\beta$ NMEs moderately

$\sim$ 30% reduction in general consistent with ab initio NMEs in ^{48}Ca, ^{76}Ge

Good agreement in benchmark NMEs in light nuclei with ab initio calculations

Light-neutrino exchange: contact operator

Contact operator suggested to contribute to light-neutrino exchange
absorb cutoff depend. of two-nucleon decay amplitude: high-energy neutrinos

$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M^{0\nu}_{\text{long}} + M^{0\nu}_{\text{short}}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2},$$

Cirigliano et al. PRL120 202001(2018)

$$M^{0\nu}_{\text{short}} \equiv \frac{1.2A^{1/3}\,\text{fm}}{g_A^2} \langle 0_f^+ | \sum_{n.m} \tau_m^- \tau_n^- \, \mathbb{1} \left[\frac{2}{\pi} \int j_0(qr)\, 2g_\nu^{\text{NN}}\, g(p/\Lambda)\, p^2 dp\right] |0_i^+\rangle,$$

$$M^{0\nu}_{\text{GT}} \simeq \frac{1.2A^{1/3}\,\text{fm}}{g_A^2} \langle 0_f^+ | \sum_{n.m} \tau_m^- \tau_n^- \, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \left[\frac{2}{\pi} \int j_0(qr)\, \frac{1}{p^2}\, g_A^2\, f^2(p/\Lambda_A)\, p^2 dp\right] |0_i^+\rangle$$

Unknown value (and sign) of the hadronic coupling g_ν^{NN}!

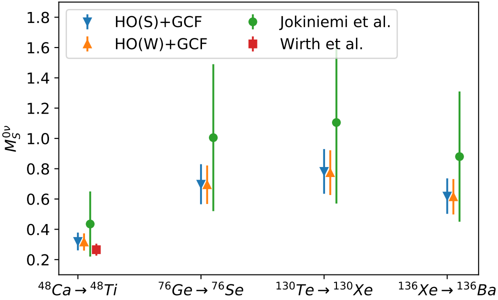
Lattice QCD calculations can obtain value of g_ν^{NN}
Davoudi, Kadam, Phys. Rev. Lett. 126, 152003 (2021), PRD105 094502('22)
or match $nn \to pp + ee$ amplitude calculated with approximate QCD methods
Cirigliano et al. PRL126 172002 (2021), JHEP 05 289 (2021)
or charge-independence breaking of nuclear Hamiltonians
Cirigliano et al. PRC100, 055504 (2019)

Short-range NME: GCF + shell model

Shell model with short-range correlations from QMC using the GCF give consistent contribution of new term M_S

$\sim$ 25% impact of short-range NME in GCF + shell model obtained with g_ν^{NN} from AV18 CIB term

consistent with 43% effect in IM-GCM for ^{48}Ca using synthetic data on $nn \to pp + ee$ decay Wirth et al. PRL127 242502 (2021)



Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021): **L. Jokiniemi's talk Thursday**

Systematic shell-model calculations

Explore systematic shell-model matrix elements
in configuration spaces relevant for $0\nu\beta\beta$ decay searches

- $^{46-58}$Ca, $^{50-58}$Ti, and $^{54-60}$Cr
  in pf-shell with KB3G and GXPF1B interactions
- $^{72-76}$Ni, $^{74-80}$Zn, $^{76-82}$Ge, and ^{82,84}Se
  in $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$, and $0g_{9/2}$ configuration space
  with GCN2850, JUN45, and JJ4BB interactions
- $^{124-132}$Sn, $^{130-134}$Te, and ^{134,136}Xe
  in $1d_{5/2}$, $0g_{7/2}$, $2s_{1/2}$, $1d_{3/2}$, and $0_{h11/2}$ configuration space
  with the GCN5082 and QX interactions

Overall, $\sim 20-40$ different calculations for each configuration space

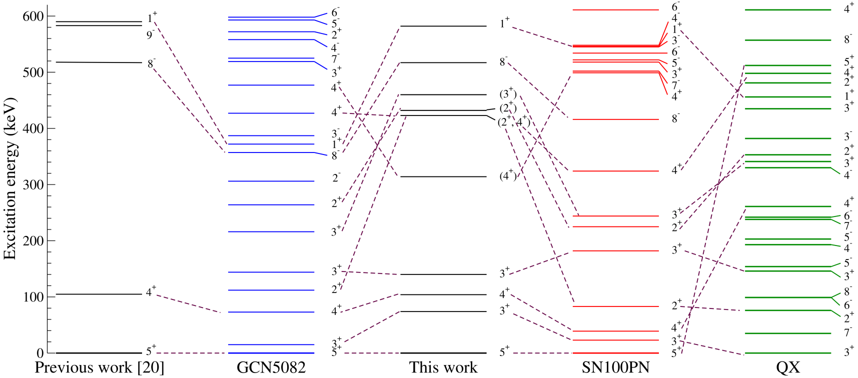
Complementary approach to randomly varying nuclear interaction

Horoi et al. PRC 106, 054302 (2022), PRC 107, 045501 (2023)

^{136}Cs experimental spectrum

While all these interactions are well, tested recent data on ^{136}Cs suggests GCN5082 results agree better with experiment than QX

Rebeiro, Triambak et al. arXiv:2301.11371



QX gives systematically smaller ^{136}Xe $0\nu\beta\beta$-decay nuclear matrix elements

Double Gamow-Teller strengths and $\beta\beta$ decay

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

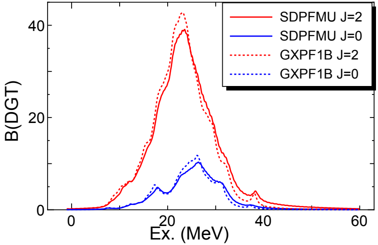
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

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

Shell model calculation

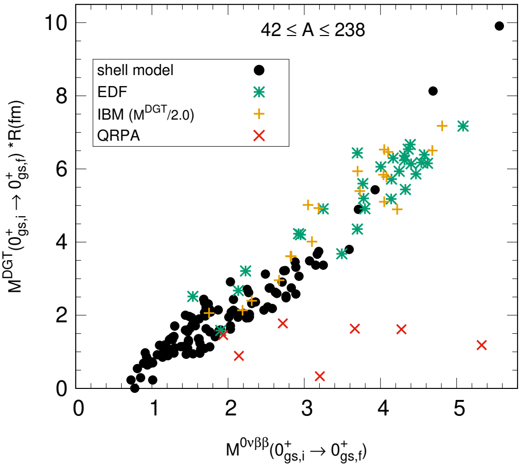
Shimizu, JM, Yako, PRL120 142502 (2018)



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

Correlation of $0\nu\beta\beta$ decay to DGT transitions

Double GT transition to ground state
good linear correlation with $0\nu\beta\beta$ decay NMEs



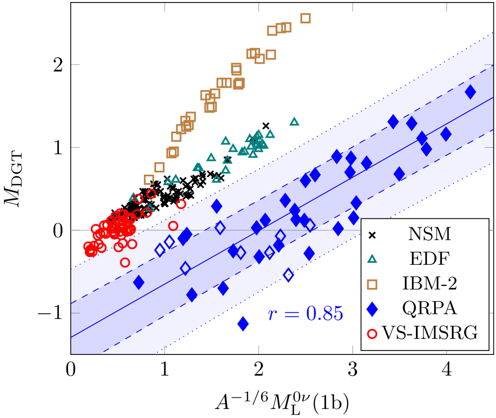
Double Gamow-Teller correlation with $0\nu\beta\beta$ decay holds across nuclear chart
Shimizu, JM, Yako
PRL120 142502 (2018)

Common to shell model energy-density functionals interacting boson model, disagreement to QRPA
Also correlation in VS-IMSRG (but weaker)
Yao et al. PRC106 014315(2022)

Experiments at RIKEN, INFN, RCNP?
access DGT transitions

Correlation of $0\nu\beta\beta$ decay to DGT in QRPA

In QRPA, g_{pp} parameter
typically fitted to reproduce $2\nu\beta\beta$ half-life of measured transitions
but actually some tension between g_{pp} values to reproduce single-β decays
Faessler et al., J. Phys. G 35, 075104 (2008)



Jokiniemi, JM, PRC 107 044316 (2023)

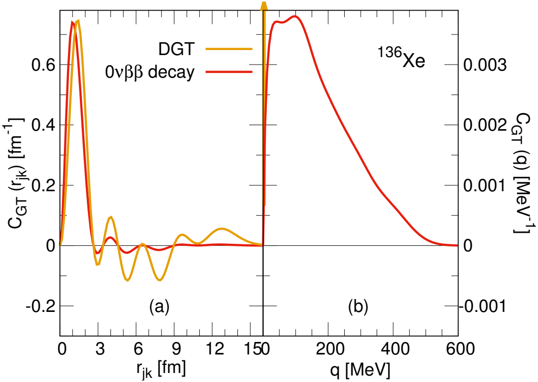
Perform QRPA calculations with range of $g_{pp} = (0.6 - 0.9)$

Correlation between DGT and $0\nu\beta\beta$ NMEs!
but different than for other many-body methods

Partially caused by relevance of $J > 1$ intermediate states in QRPA compared to eg shell model
Ejiri et al. Phys. Rept. 797 1 (2019)
Horoi et al, PRC 93, 044334 (2016)

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

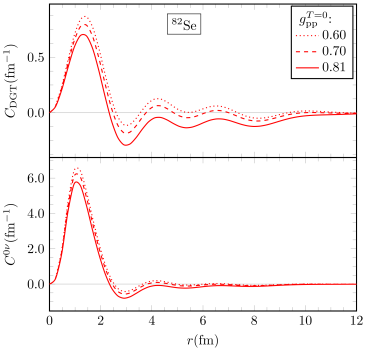
Long-range part dominant in QRPA DGT matrix elements

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)



Jokiniemi, JM, PRC 107 044316 (2023)

$0\nu\beta\beta$ 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

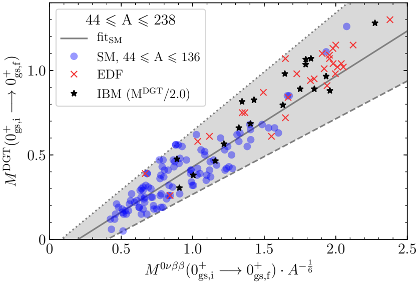
Long-range part dominant in QRPA DGT matrix elements

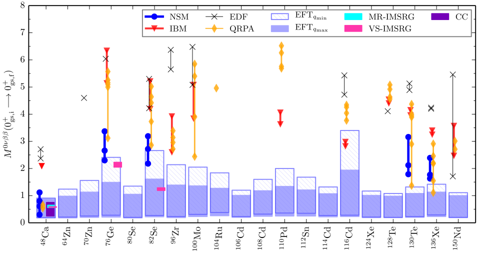
Shimizu, JM, Yako, PRL120 142502 (2018)

$0\nu\beta\beta$ decay NMEs in ET of β decay

Effective theory of β decay can calculate DGT with uncertainties
(similar to calculation of $2\nu\beta\beta$, no energy denominator)
DGT vs 0nbb correlation $\Rightarrow$ predict $0\nu\beta\beta$ NMEs with uncertainties

Because ET couplings fitted to β decay and GT strengths
correct shell model DGT NMEs in correlation
by "quenching" factor for these observables: $q = 0.42 - 0.65$



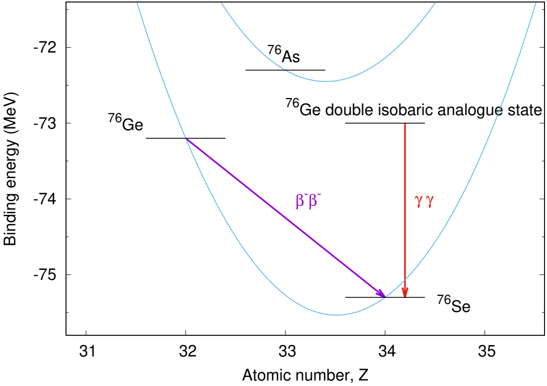


Brase, JM, Coello Pérez, Schwenk, PRC106, 034309 (2022)

$\gamma\gamma$ decay of the DIAS of the initial $\beta\beta$ nucleus

Explore correlation between $0\nu\beta\beta$ and $\gamma\gamma$ decays,
focused on double-M1 transitions

$$M^{\gamma\gamma}_{M1\,M1} = \sum_k \frac{\langle 0^+_f | \sum_n (g^l_n \boldsymbol{l}_n + g^s_n \boldsymbol{\sigma}_n)^{IV} | 1^+_k(\text{IAS}) \rangle \langle 1^+_k(\text{IAS}) | \sum_m (g^l_m \boldsymbol{l}_m + g^s_m \boldsymbol{\sigma}_m)^{IV} | 0^+_i(\text{DIAS}) \rangle}{E_k - (E_i + E_f)/2}$$



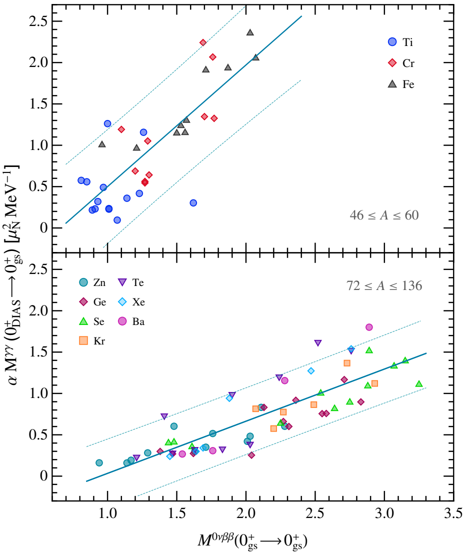
Similar initial and final states
but both in same nucleus
for electromagnetic transition

M1 and GT operators similar,
physics of spin operator
M1 also angular momentum

Different energy denominator

Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Correlation between $M1M1$ and $0\nu\beta\beta$ NMEs



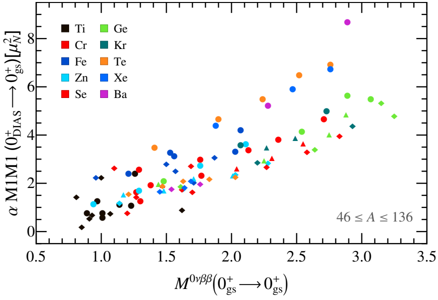
Good correlation between $M1M1$ same-energy photons and shell-model $0\nu\beta\beta$ NMEs

A dependence:
energy denominator
dominant states at higher energy in heavier nuclei

Overall, study $\sim$ 50 transitions
several nuclear interactions for each of them

Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Intermediate states of the $M1M1$ transition



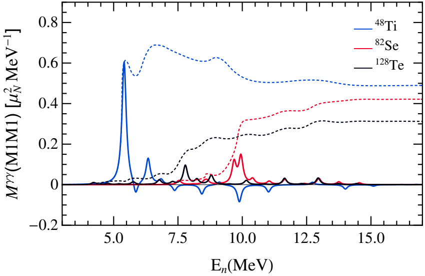
When energy denominators are (artificially) removed, same correlation across the nuclear chart

Romeo, JM, Peña-Garay

PLB 827 136965 (2022)

Dominant intermediate states lower energies for lighter nuclei, otherwise similar energies

One or few intermediate states typically dominate the transition

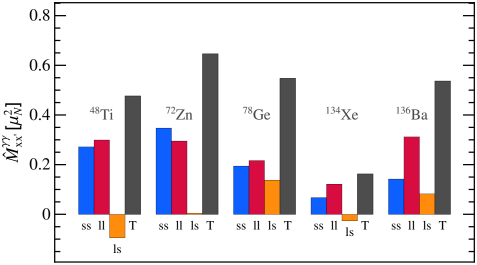


Spin, angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{\gamma\gamma} = \hat{M}_{ss} + \hat{M}_{ll} + \hat{M}_{ls}$$

spin, angular momentum and interference components



Spin, angular momentum terms strikingly similar, always carry same sign

Interference term can cancel the other two but always much smaller

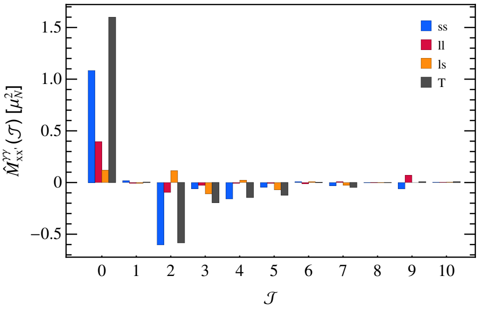
Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Total angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{\gamma\gamma}(\mathcal{J}) = \hat{M}_{ss}(\mathcal{J}) + \hat{M}_{ll}(\mathcal{J}) + \hat{M}_{ls}(\mathcal{J})$$

spin, angular momentum and interference components
and total angular momentum of the nucleons involved in the transition



Dominance of $\mathcal{J} = 0$ terms
for spin and orbital contributions
just like in $0\nu\beta\beta$ decay

Cancellation from $\mathcal{J} > 0$ terms
less pronounced in orbital part

Explains similar behaviour of spin
and orbital components:

$$s_1\, s_2 = \mathcal{S}^2 - 3/2 < 0$$

$$l_1\, l_2 = \mathcal{L}^2 - l_1^2 - l_2^2 < 0$$

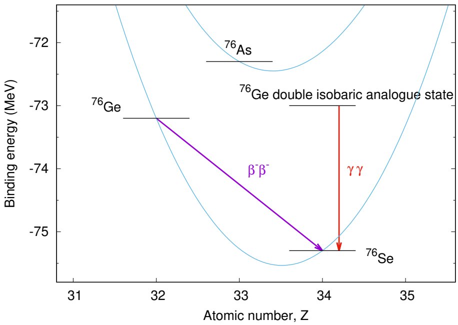
Romeo et al. PLB 827 136965 (2022)

Experimental feasibility of $\gamma\gamma$ decay?

$\gamma\gamma$ decays are very suppressed with respect to γ decays
just like $\beta\beta$ decays are much slower than β decays

$\gamma\gamma$ decays have been observed recently
in competition with γ decays

Waltz et al. Nature 526, 406 (2015), Soderstrom et al. Nat. Comm. 11, 3242 (2020)



Outlook:

Study in detail leading
decay channels for $M1M1$ decay
in DIAS of $\beta\beta$ nuclei

Particle emission $M1$, $E1$ decay:
BR $\sim 10^{-7} - 10^{-8}$

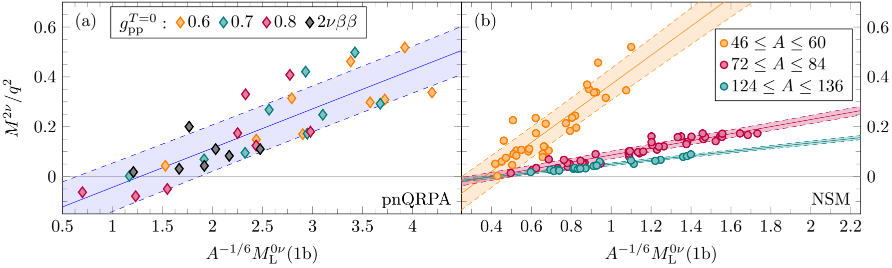
Experimental proposal for ^{48}Ti
by Valiente-Dobón et al.

Valiente-Dobón, Romeo et al., in prep

Correlation of $0\nu\beta\beta$ decay and $2\nu\beta\beta$ decay

Good correlation between 2ν and 0ν modes of $\beta\beta$ decay
in nuclear shell model (systematic calculations of different nuclei)
and QRPA calculations (decays of $\beta\beta$ emitters with different g_{pp} values)

Similar but not common correlation, depends on mass for shell model
$0\nu\beta\beta - 2\nu\beta\beta$ correlation also observed in ^{48}Ca, ^{136}Xe
Horoi et al. PRC 106, 054302 (2022), PRC 107, 045501 (2023)



Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

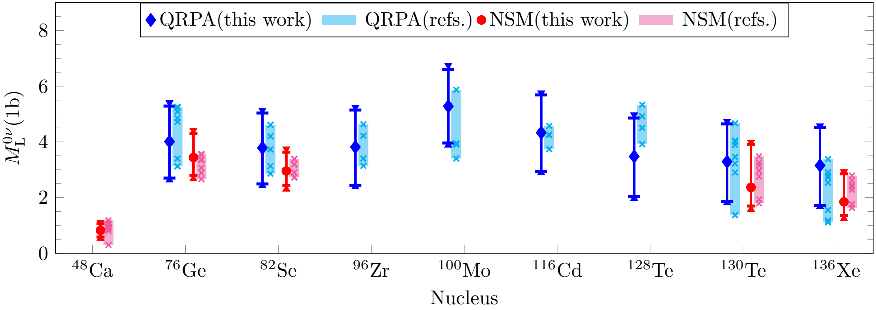
Use $2\nu\beta\beta$ data to predict $0\nu\beta\beta$ NMEs!

$0\nu\beta\beta$ NMEs from $2\nu\beta\beta - 0\nu\beta\beta$ correlation

NMEs consistent with previous nuclear shell model, QRPA results

Theoretical uncertainty involves
systematic calculations covering dozens of nuclei and interactions
error of each calculation (eg quenching) and experimental $2\nu\beta\beta$ error

Previous theoretical uncertainty mostly ignored: collection of calculations



Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

2b currents in $0\nu\beta\beta$ decay

In $0\nu\beta\beta$ decay, two weak currents lead to four-body operator when including the product of two 2b currents: computational challenge

Approximate 2b current as effective 1b current normal ordering with respect to a Fermi gas

JM, Gazit, Schwenk, PRL107 062501(2011)

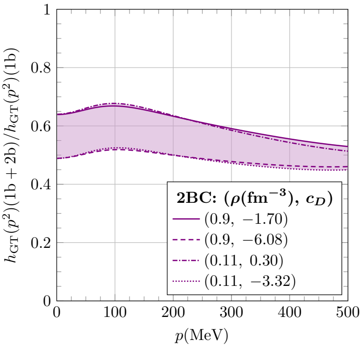
Normal-odering approximation works remarkably well for β decay ($q = 0$)

Gysbers et al. Nature Phys. 15 428 (2019)

Some reduction of quenching due to 2b currents at $p \sim m_\pi$ relevant for $0\nu\beta\beta$ decay

Hoferichter, JM, Schwenk

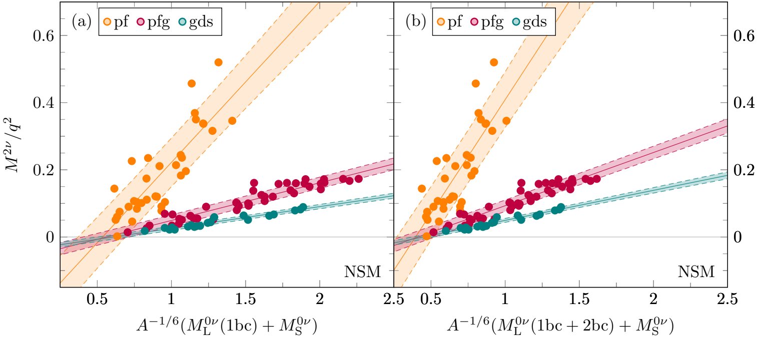
PRD102 074018 (2020)



Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

Correlation of $0\nu\beta\beta$ decay to $2\nu\beta\beta$: general case

A good correlation between $2\nu\beta\beta$ and $0\nu\beta\beta$
also appears when we include to the calculation of $0\nu\beta\beta$ NMEs
2b currents and the short-range nuclear matrix element



Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

Use $2\nu\beta\beta$ data to predict $0\nu\beta\beta$ NMEs with 2b currents, short-range NME

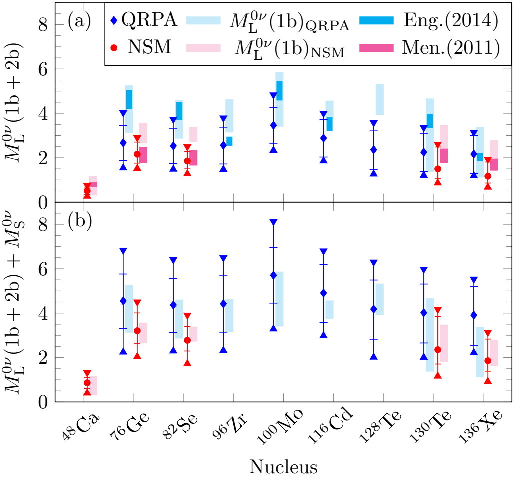
$0\nu\beta\beta$ NMEs from correlation: 2bc, short-range

$0\nu\beta\beta$ NMEs including 2b currents and short-range NME obtained from $0\nu\beta\beta - 2\nu\beta\beta$ correlation and $2\nu\beta\beta$ data

Theoretical uncertainty due to correlation, calculation uncertainties: quenching, 2bc, short-range NME coupling (dominant uncertainty)

First complete estimation of $0\nu\beta\beta$ nuclear matrix elements with theoretical uncertainties

Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)



Summary

Calculations of $0\nu\beta\beta$ NMEs
challenge nuclear many-body methods,
searches demand reliable NMEs

Ab initio results suggest reduced NMEs
due to nuclear correlations (eg via GCF)
and two-body currents
Likely enhancement by short-range NME

Double Gamow-Teller transitions,
electromagnetic $M1M1$ decay of DIAS
good correlation with $0\nu\beta\beta$ NMEs

Good $0\nu\beta\beta - 2\nu\beta\beta$ correlation
exploit $2\nu\beta\beta$ data to obtain $0\nu\beta\beta$ NMEs
with theoretical uncertainties