

Nuclear theory for $\beta\beta$ decay

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Irène Joliot-Curie Lab (Orsay) $\beta\beta$ decay Workshop
16th October 2020



UNIVERSITAT DE
BARCELONA



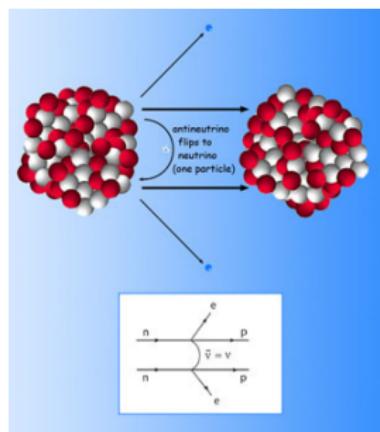
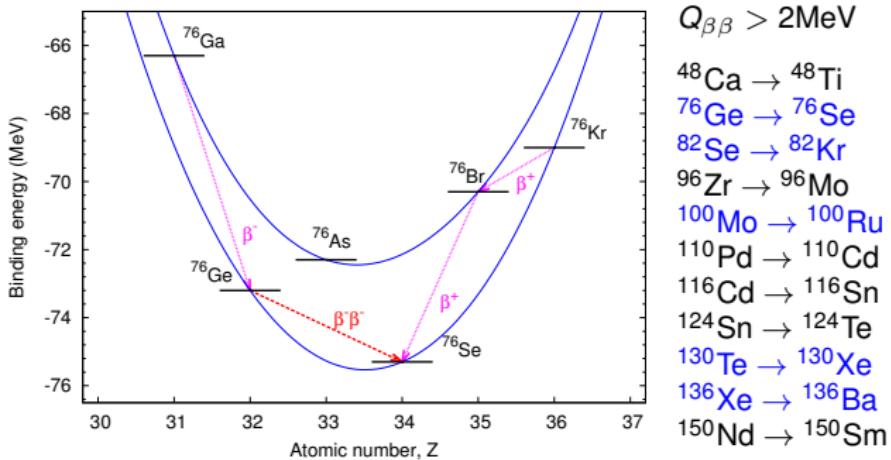
Investigación
Programa
Ramón y Cajal



Nuclear $\beta\beta$ decay

$\beta\beta$ decay second order process observable if β -decay is energetically forbidden or hindered by large ΔJ

Neutrinoless double-beta decay ($0\nu\beta\beta$):
Lepton-number violation, Majorana nature of neutrinos



Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

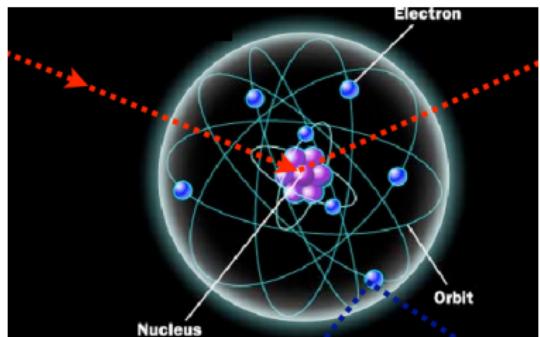
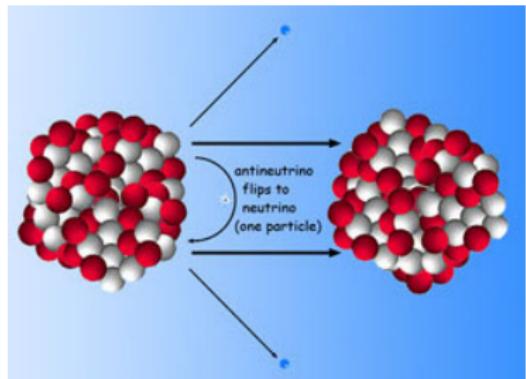
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

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

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

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

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

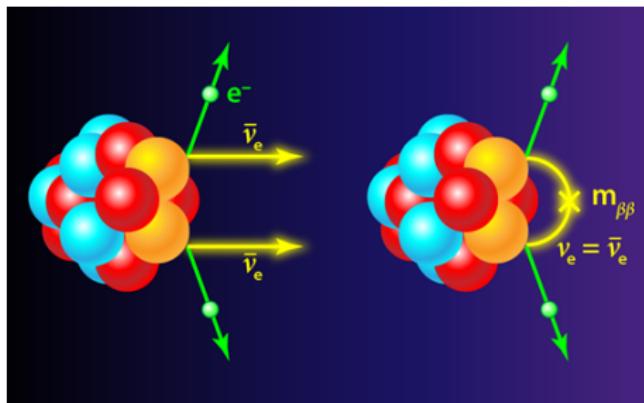


Calculating nuclear matrix elements

Nuclear matrix elements needed in low-energy new physics searches

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

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

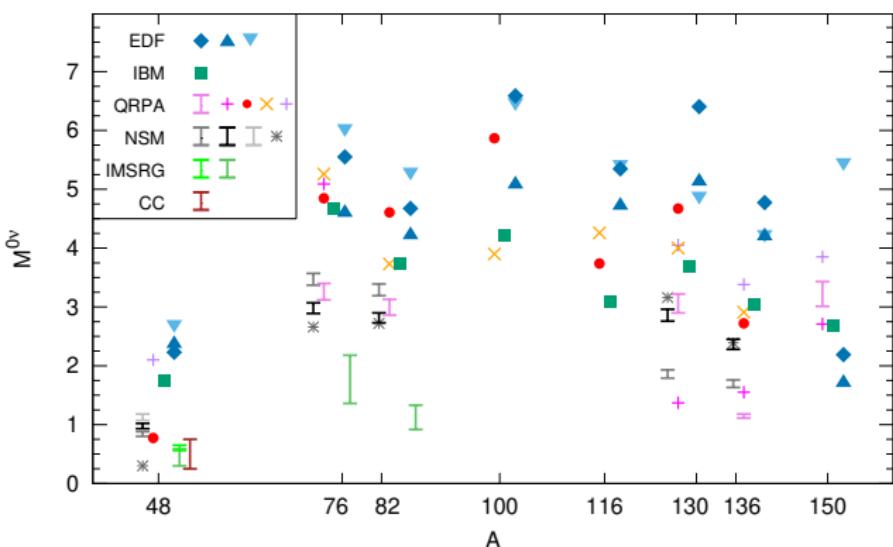


$0\nu\beta\beta$ decay nuclear matrix elements

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



EDF: large NMEs

QRPA: wider range

NSM: small NMEs

IMSRG ab initio
 $^{48}\text{Ca}, ^{76}\text{Ge}, ^{82}\text{Se}$ NME

Yao et al.

PRL 124 232501 (2020)

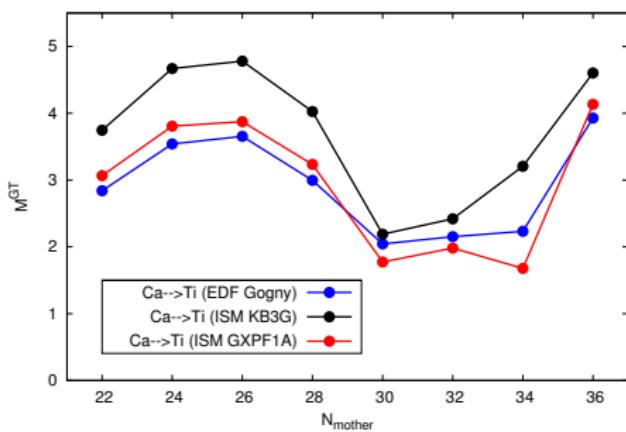
Bellley et al. arXiv:2008.06588

Novario et al. arXiv:2008.09696

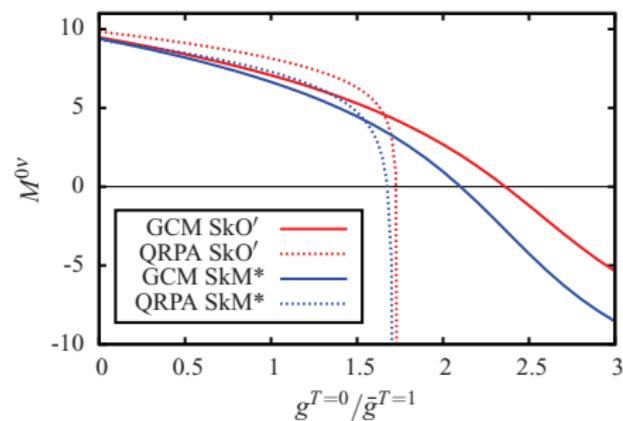
Correlations: proton-neutron pairing

$0\nu\beta\beta$ NMEs agree without nuclear correlations (very simplistic nuclei)

NMEs too large if proton-neutron pairing correlations are neglected



JM et al. PRC90 024311(2014)



Hinohara, Engel PRC90 031301 (2014)

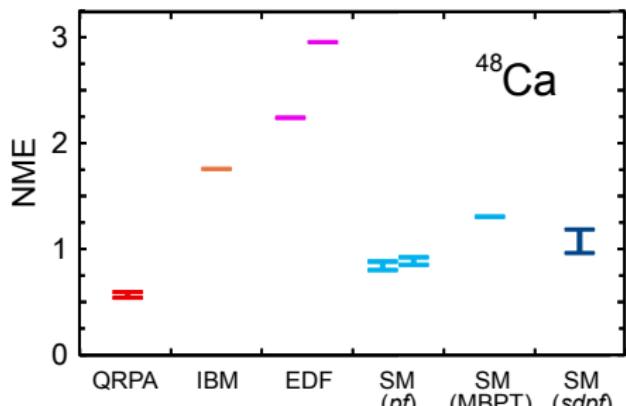
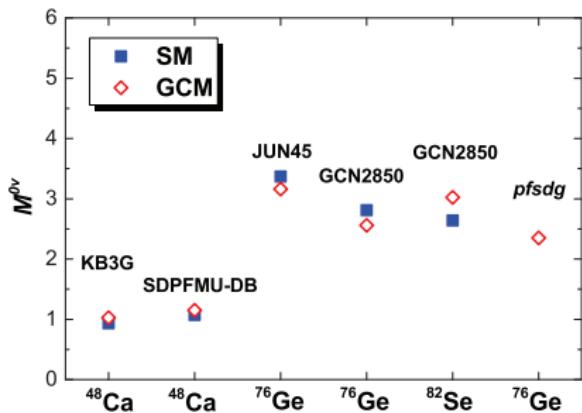
Related to approximate $SU(4)$ symmetry of the $\sum H(r)\sigma_i\sigma_j\tau_i\tau_j$ operator

Correlations: large configuration space

^{48}Ca extended configuration space
from pf to $sdpf$, 4 to 7 orbitals
dimension 10^5 to 10^9

^{48}Ca 0_2^+ state lowered by 1.3 MeV
nuclear matrix elements
enhanced only moderately 30%

Iwata et al. PRL116 112502 (2016)



Also small effect of large space
with perturbative calculation

Coraggio et al. PRC 101 044315 (2020)

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

Jiao et al. PRC96 054310 (2017)

Correlations: IMSRG NME for ^{48}Ca

Multi-reference calculation:

correlations systematically built on collective reference state

Generator coordinate method: deformation, isoscalar pairing

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

Best IMSRG calculation
reproduces EM
transitions in ^{48}Ti

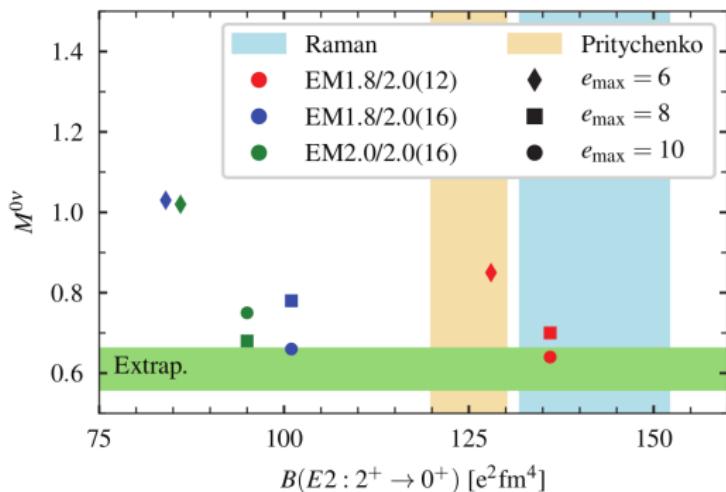
NME $\sim 0.4/30\%$ smaller
than nuclear shell model

Yao et al.

PRL 124 232501 (2020)

Consistent with
coupled cluster NME

Novario et al. arXiv:2008.09696



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

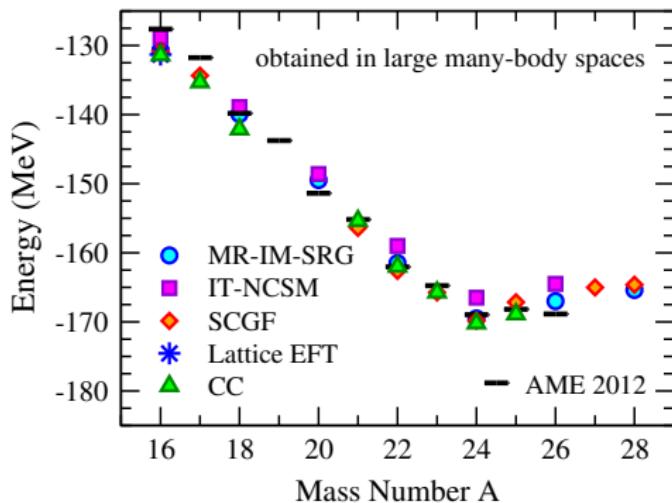
Hergert et al. PRL110 242501(2013)

Self-consistent Green's
function

Cipollone et al. PRL111 062501(2013)

Coupled-clusters

Jansen et al. PRL113 142502(2014)

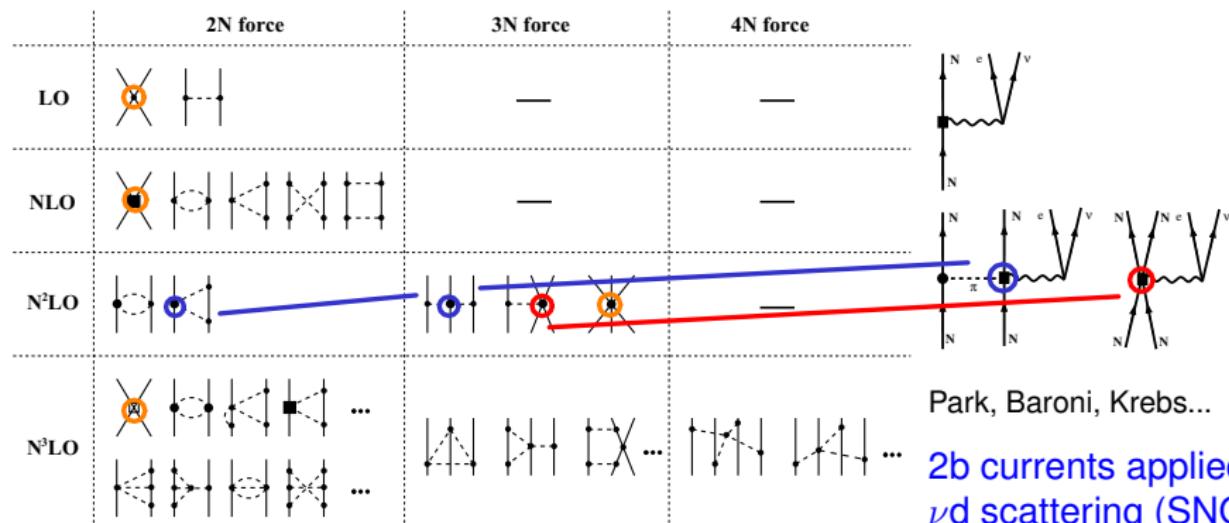


Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents

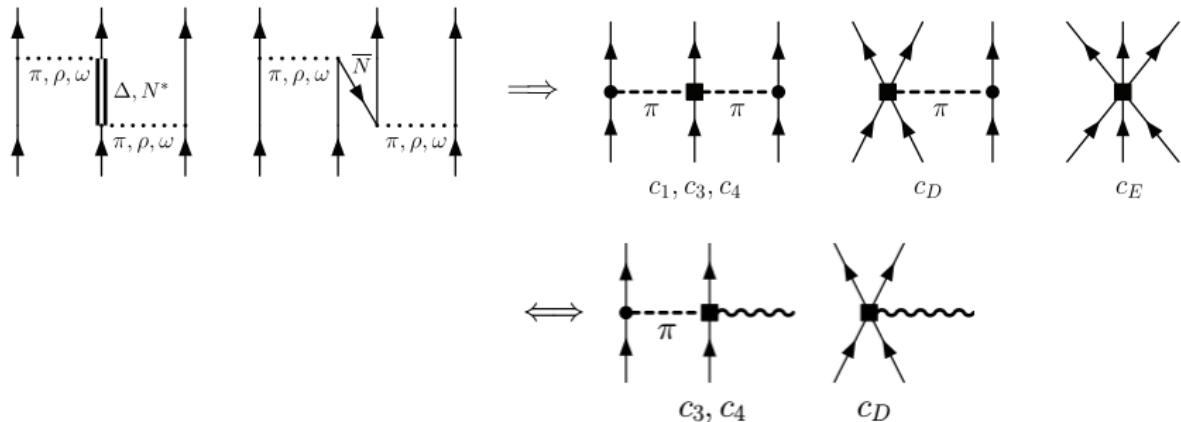


Three-nucleon forces, two-nucleon currents

Forces between 3 nucleons, external probe couplings to 2 nucleons known in nuclear theory for a long time

Fujita and Miyazawa PTP17 (1957), Towner Phys. Rep. 155 (1987)...

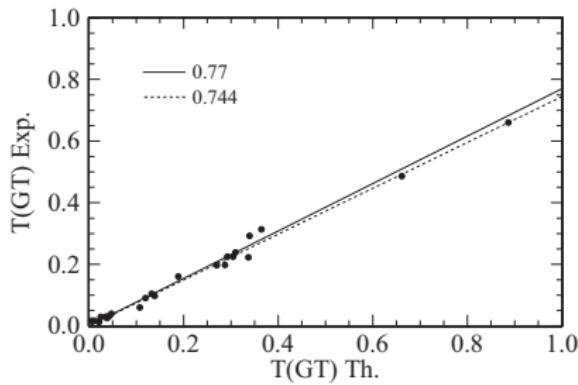
3N forces, 2b currents needed because of missing degrees of freedom



3N forces and 2b currents should be considered in nuclear structure, electromagnetic and weak transition calculations

Solution of the “ g_A quenching” puzzle

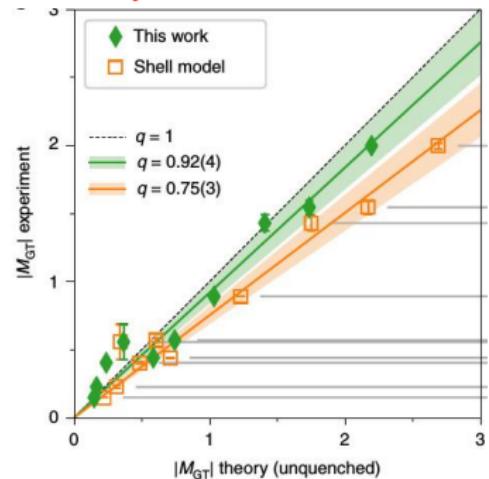
β decays (e^- capture) challenge for nuclear theory



Martinez-Pinedo et al. PRC53 2602(1996)

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

Phenomenological models
need $\sigma_i \tau$ “quenching”

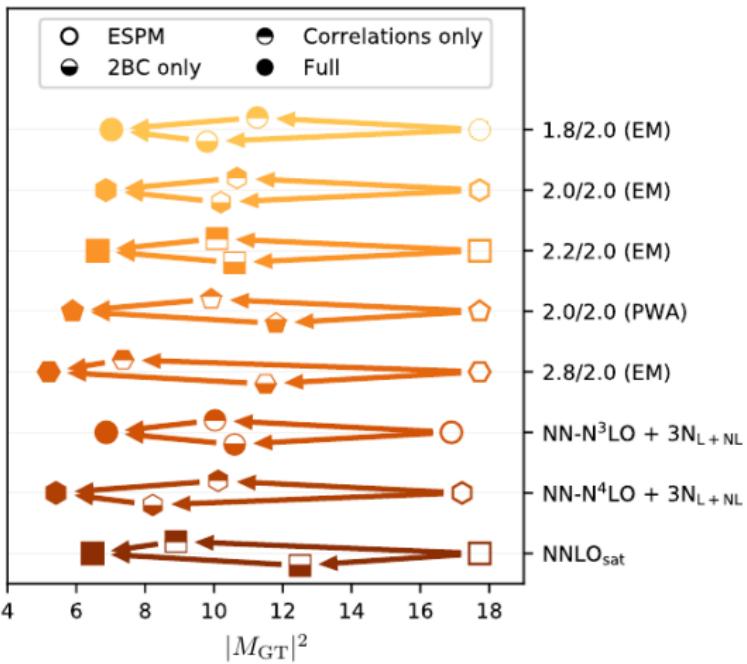


Gysbers et al. Nature Phys. 15 428 (2019)

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

Origin of β decay “quenching”

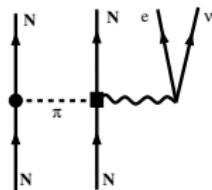
Which are main effects missing in conventional β -decay calculations?



Relatively similar
and complementary
impact of

- nuclear correlations
- meson-exchange currents

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



VS-IMSRG $0\nu\beta\beta$ NME for ^{76}Ge , ^{82}Se

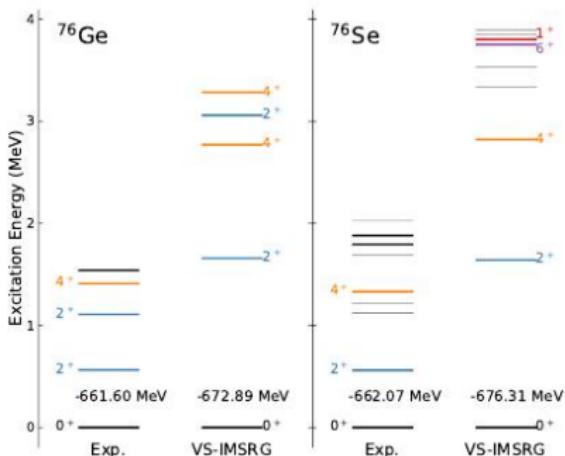
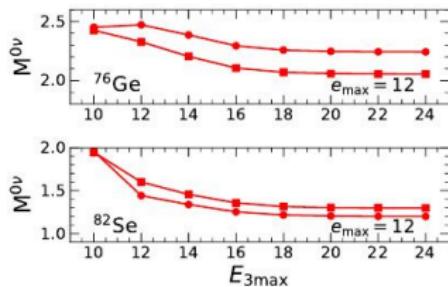
VS-IMSRG reaches ^{76}Ge
one of the targets used in
most advanced experiments
(GERDA, MAJORANA)

VS-IMSRG NME converged
in 3N matrix elements included
Miyagi et al.

Excitation spectra too spread
quadrupole correlations
not properly captured?

NME $\sim 20\% / 50\%$ smaller
than nuclear shell model

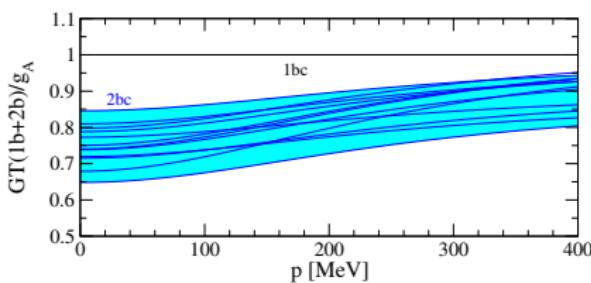
Bellley et al. arXiv:2008.06588



2b currents in $\beta\beta$ 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

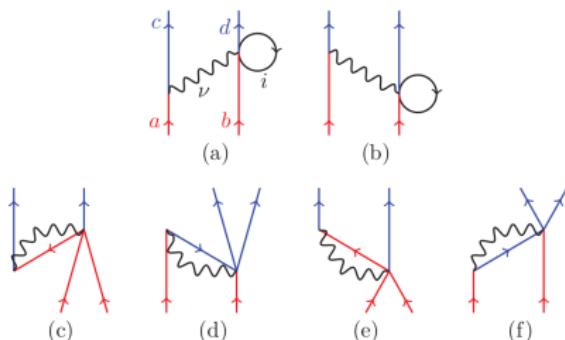


Quenching reduced to $\sim 20\%$

at $p \sim m_\pi$ for $0\nu\beta\beta$ decay

JM et al. PRL107 062501(2011)

Approximate 4b operator
as effective 3b operator



Estimated effect $\sim 10\%$

Wang et al. PRC98 031301 (2018)

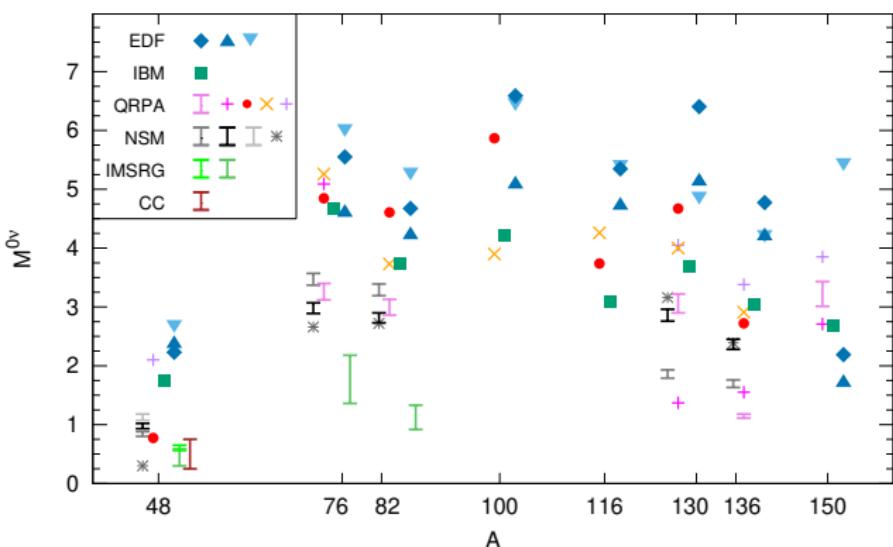
Estimations suggest that 2b currents smaller in $0\nu\beta\beta$ than β decay

$0\nu\beta\beta$ 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
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Yao et al.

PRL 124 232501 (2020)

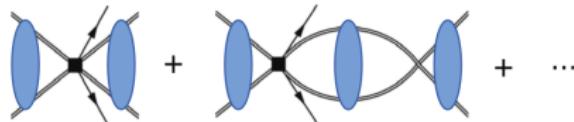
Bellley et al. arXiv:2008.06588

Novario et al. arXiv:2008.09696

Light-neutrino exchange: new contact operator

Contact operator suggested to contribute to light-neutrino exchange
to absorb cutoff dependence of two-nucleon decay amplitude

$$T_{1/2}^{-1} = G_{01} (g_A^2 M^{0\nu} + g_\nu^{\text{NN}} m_\pi^2 M_{\text{cont}}^{0\nu})^2 \frac{m_{\beta\beta}^2}{m_e^2}, \quad \text{Cirigliano et al. PRL120 202001(2018)}$$



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

Could be determined experimentally, by Lattice QCD or analytically

$$M_{\text{cont}}^{0\nu} \equiv \frac{1}{m_\pi^2} \frac{1.2 A^{1/3} \text{ fm}}{g_\nu^{\text{NN}}} \langle 0_f^+ | \sum_{n,m} \tau_m^- \tau_n^- \mathbb{1} \left[\frac{2}{\pi} \int j_0(qr) 2g_\nu^{\text{NN}} f^2(p/\Lambda_V) p^2 dp \right] | 0_i^+ \rangle,$$

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

regularized by dipole form factor $f(p/\Lambda)$, $\Lambda \sim 1 \text{ GeV}$

Short-range NME in heavy nuclei

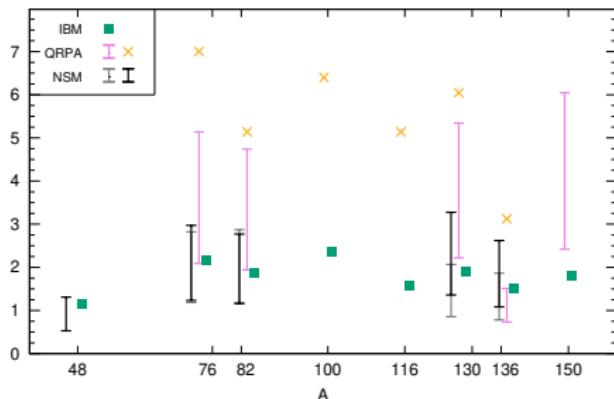
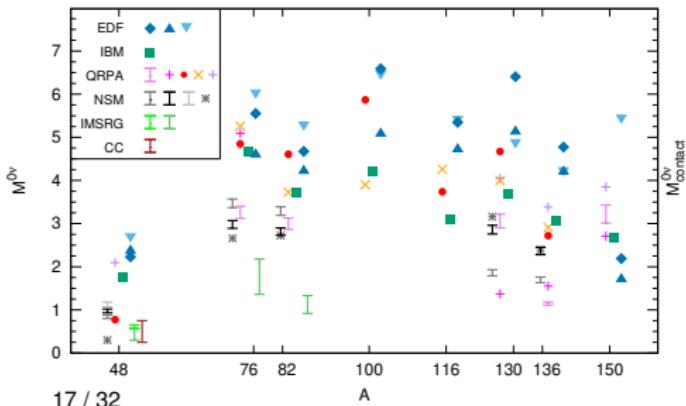
Modified decay rate: $T_{1/2}^{-1} = G_{01} (g_A^2 M^{0\nu} + g_\nu^{\text{NN}} m_\pi^2 M_{\text{cont}}^{0\nu})^2 \frac{m_{\beta\beta}^2}{m_e^2}$

Short-range nuclear matrix elements:

Similar disagreement between NSM, QRPA, IBM, EDF... calculations as standard long-range nuclear matrix elements

Large error bars because uncertainty in short-range dynamics

Cruz-Torres et al. PLB 785 304 (2018)



Short-range matrix element: relative impact

Modified decay rate:

$$T_{1/2}^{-1} = G_{01} (g_A^2 M^{0\nu} + g_\nu^{\text{NN}} m_\pi^2 M_{\text{cont}}^{0\nu})^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

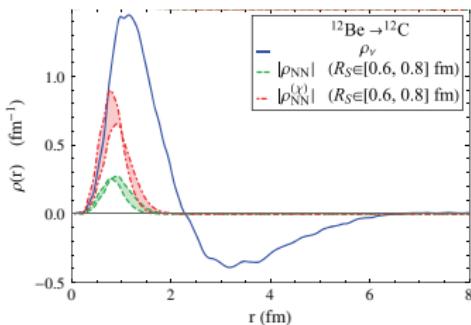
Assume

$$g_\nu^{\text{NN}} \sim 1 \text{ fm}^2$$

Cirigliano et al.

PRC100 055504 (2019)

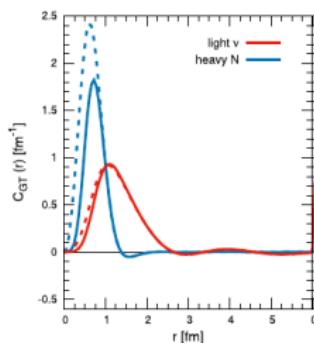
$\sim 10\% - 30\%$ correction for NSM ${}^{76}\text{Ge}$ NME, smaller than
 $\sim 75\%$ correction for QMC ${}^{12}\text{Be}$ NME



Cirigliano et al. PRL120 202001(2018)

TABLE II. Values of $\mathcal{C}_1 + \mathcal{C}_2$ obtained from the CIB contact interactions in various chiral potentials.

Model	Ref.	R_S (fm)	C_0^{IT} (fm^2)	$(\mathcal{C}_1 + \mathcal{C}_2)/2$ (fm^2)	Model	Ref.	Λ (MeV)	$(\mathcal{C}_1 + \mathcal{C}_2)/2$ (fm^2)
NV-Ia*	[38]	0.8	0.0158	-1.03	Entem-Machleidt	[34]	500	-0.47
NV-IIa*	[38]	0.8	0.0219	-1.44	Entem-Machleidt	[34]	600	-0.14
NV-Ic	[38]	0.6	0.0219	-1.44	Reinert <i>et al.</i>	[39]	450	-0.67
NV-IIc	[38]	0.6	0.0139	-0.91	Reinert <i>et al.</i>	[39]	550	-1.01
				NNLO _{sat}	[37]	450	-0.39	



JM, JPG45 014003 (2018)

$0\nu\beta\beta$ mediated by BSM heavy particles

Standard Model extensions
trigger $0\nu\beta\beta$ (heavy ν , M_R ...)

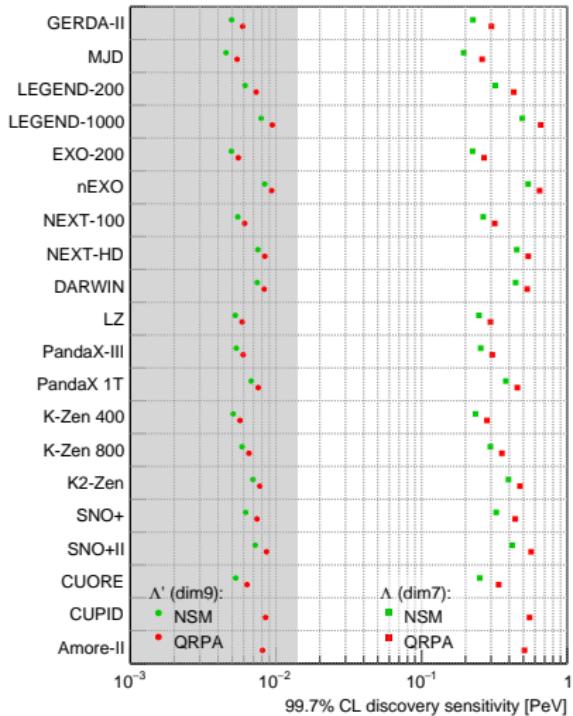
Effective field theory
master formula
Cirigliano et al JHEP 12 097 (2018)

$$T_{1/2}^{-1} = G_{01} \left(g_A^2 M^{0\nu} + g_\nu^{\text{NN}} m_\pi^2 M_{\text{cont}}^{0\nu} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

$$+ \frac{m_N^2}{m_e^2} \tilde{G} \tilde{g}^4 \tilde{M}^2 \left(\frac{v}{\Lambda} \right)^6$$

$$+ \frac{m_N^4}{m_e^2 v^2} \tilde{G}' \tilde{g}'^4 \tilde{M}'^2 \left(\frac{v}{\Lambda'} \right)^{10} + \dots,$$

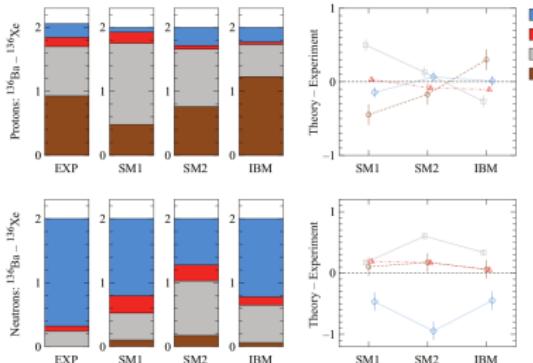
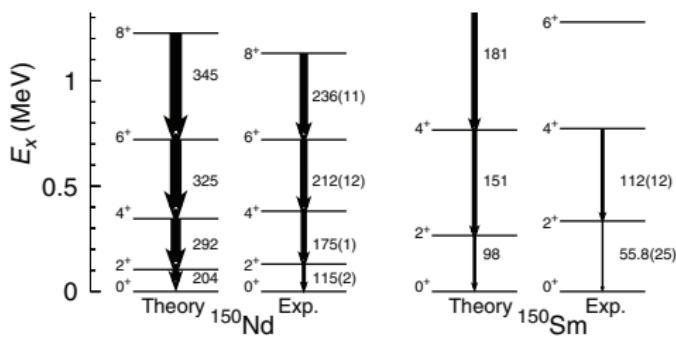
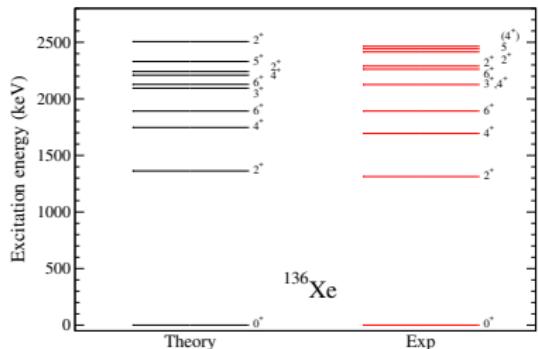
Current constraints on
dim-7 ($\sim 1/\Lambda^3$), dim-9 ($\sim 1/\Lambda^5$)
operators: $\Lambda \gtrsim 250 / 5$ TeV



Agostini, Benato, Detwiler, JM, Vissani, in prep.

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)

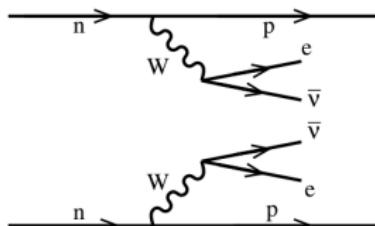
Two-neutrino $\beta\beta$ decay, 2ν ECEC

$2\nu\beta\beta$ 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

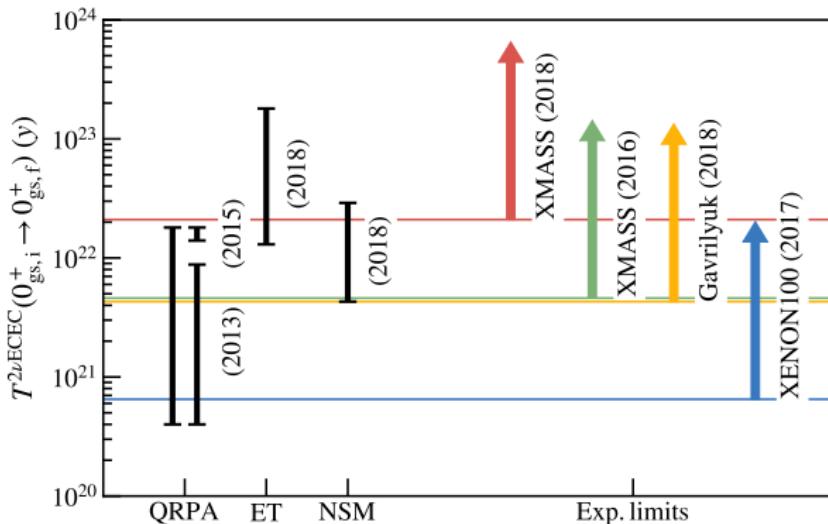
The ISM predictions for the matrix element of several 2ν double beta decay (in MeV $^{-1}$). See text for the definitions of the valence spaces and interactions.

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

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

Two-neutrino ECEC of ^{124}Xe

Predicted 2ν ECEC half-life:
shell model error bar largely dominated by “quenching” uncertainty

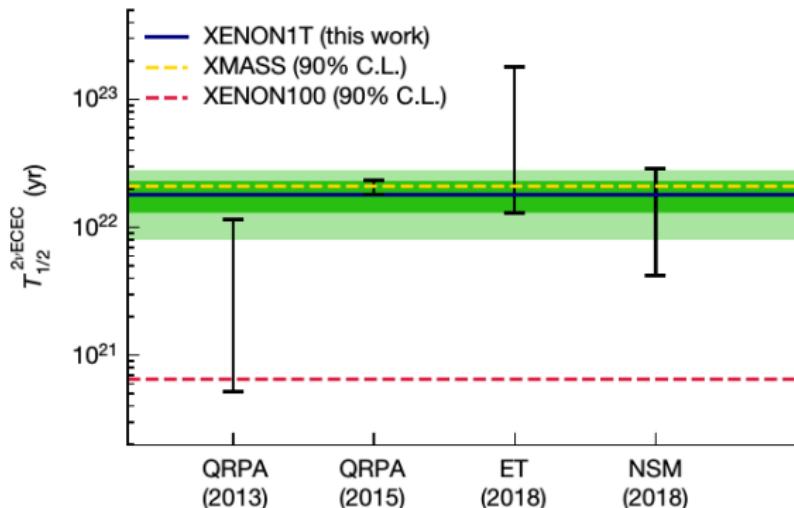


- Suhonen
JPG 40 075102 (2013)
- Pirinen, Suhonen
PRC 91, 054309 (2015)
- Coello Pérez, JM,
Schwenk
PLB 797 134885 (2019)

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

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Schwenk
PLB 797 134885 (2019)
- XENON1T
Nature 568 532 (2019)

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

Electron spectrum in two-neutrino $\beta\beta$ decay

Precise $2\nu\beta\beta$ half-life, next term in expansion of energy denominator

$$(T_{1/2}^{2\nu})^{-1} \simeq g_A^4 |(M_{GT}^{2\nu})^2 G_0^{2\nu} + M_{GT}^{2\nu} M_{GT-3}^{2\nu} G_2^{2\nu} + \dots|$$

$$M_{GT}^{2\nu} = \sum_j \frac{\langle 0_f^+ | \sum_I \sigma_I \tau_I^- | 1_j^+ \rangle \langle 1_j^+ | \sum_I \sigma_I \tau_I^- | 0_i^+ \rangle}{\Delta},$$

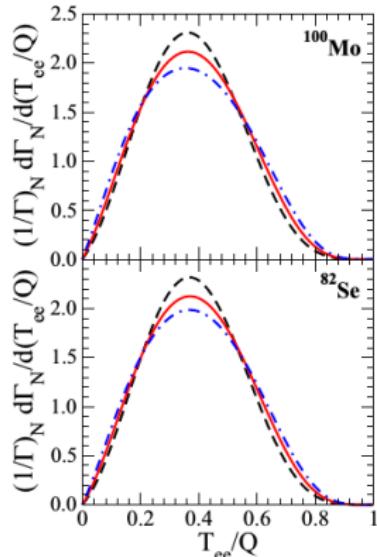
$$M_{GT3}^{2\nu} = \sum_j \frac{4 \langle 0_f^+ | \sum_I \sigma_I \tau_I^- | 1_j^+ \rangle \langle 1_j^+ | \sum_I \sigma_I \tau_I^- | 0_i^+ \rangle}{\Delta^3},$$

$$\Delta = [E_j - (E_i + E_f)/2]/m_e$$

Electron differential decay rate:

$$\frac{d\Gamma^{\beta\beta}}{dT_{ee}} \sim \frac{dG_0}{dT_{ee}} + \frac{M_{GT}^{2\nu}}{M_{GT-3}^{2\nu}} \frac{dG_2}{dT_{ee}}$$

Exp. sensitivity to $\xi_{31}^{2\nu} = M_{GT-3}^{2\nu}/M_{GT}^{2\nu}$

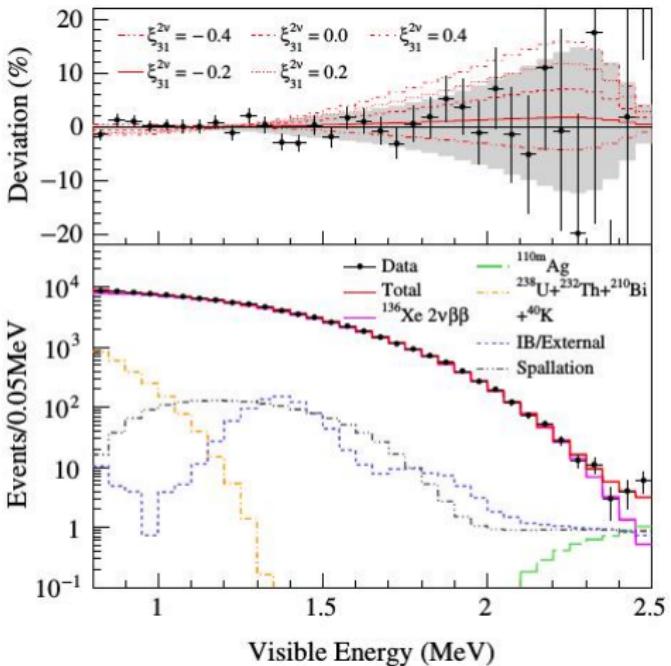


Šimkovic et al.

PRC98 064325 (2018)

Electron spectrum in ^{136}Xe $\beta\beta$ decay

Present $0\nu\beta\beta$
experiments observe
 ~ 10000 $2\nu\beta\beta$ decays,
major background

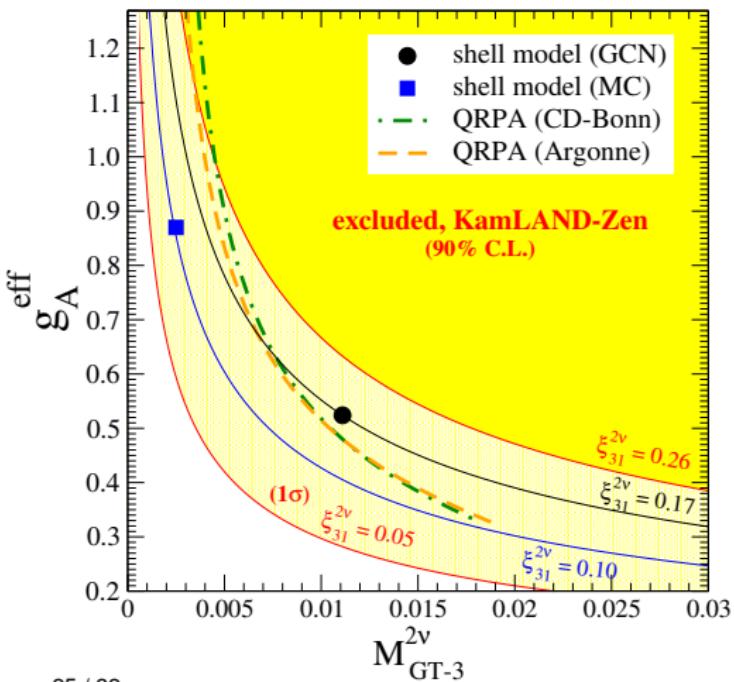


KamLAND-Zen $2\nu\beta\beta$
analysis excludes larger
values of $\xi_{31}^{2\nu}$

KamLAND-Zen, PRL122 192501 (2019)

Ratio of leading/subleading $\beta\beta$ matrix elements

Shape of $\beta\beta$ spectrum constrains matrix element ratio $\xi_{31}^{2\nu} = M_{GT-3}^{2\nu}/M_{GT}^{2\nu}$



Theory deficiencies in $M_{GT}^{2\nu}$
fixed adjusting g_A
("quenching")

$\xi_{31}^{2\nu}$ measurement
test theoretical models

Theory-experiment work with
KamLAND-Zen collaboration

Theory: JM, Dvornicky, Šimkovic

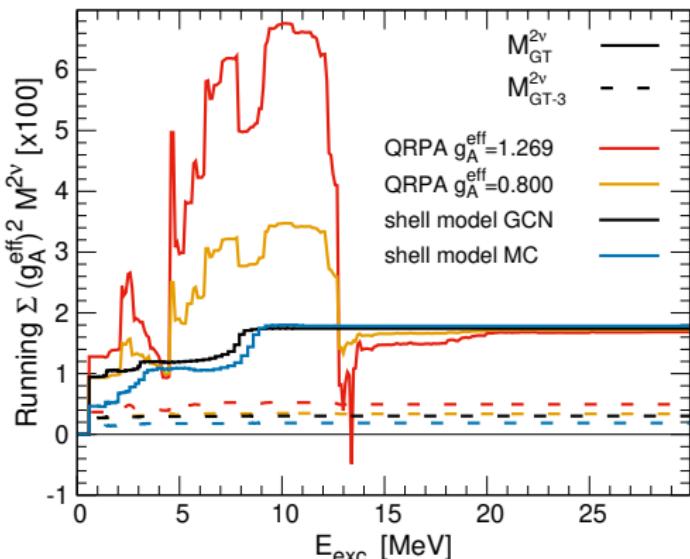
Shell model $\xi_{31}^{2\nu}$ predictions
consistent with 90% C.L. limit

KamLAND-Zen et al.

PRL122 192501 (2019)

Running of $2\nu\beta\beta$ matrix elements

Measurements of $\beta\beta$ decay spectra can test calculations with different matrix element as function of energy of intermediate state



Qualitative very different shell model vs QRPA

QRPA also quite different between different g_A^{eff} values (or diff. isoscalar pairing g_{pp})

Smaller QRPA g_A^{eff} preferred in some β -decay studies

Faessler et al.

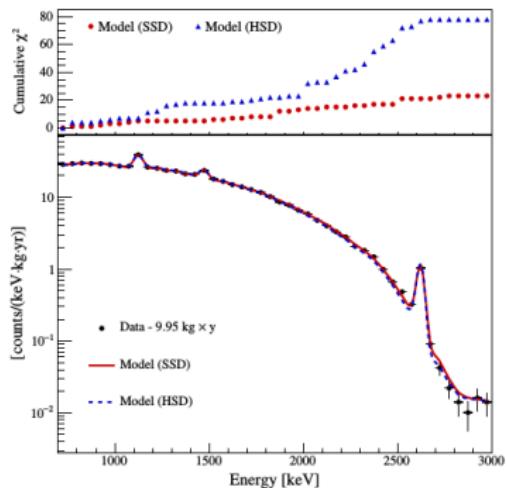
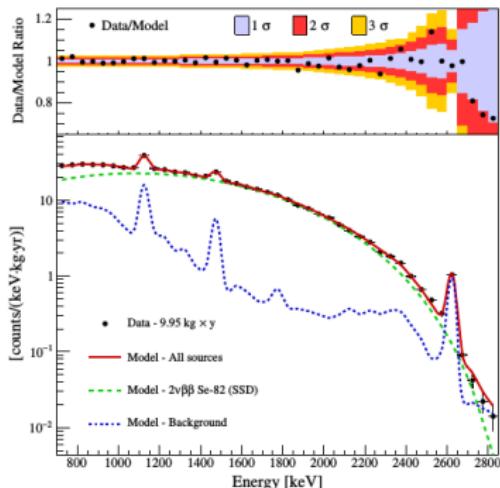
JPG 35 075104 (2008)

Likewise, $\beta\beta$ decays to excited states stronger predictions of models!

Single-state dominance in $2\nu\beta\beta$ decays

Recent CUPID-0 measurement of single-state dominance
of lowest-lying intermediate ^{82}Br 1^+ state in $^{82}\text{Se} \rightarrow ^{82}\text{Kr} + 2\bar{\nu} + 2e$ decay

CUPID-0, PRL123 262501 (2019)



Single-state dominance in ^{82}Se $2\nu\beta\beta$ decay confirmed by NEMO-3
Not predicted by any theoretical calculation

Double Gamow-Teller strength distribution

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

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

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

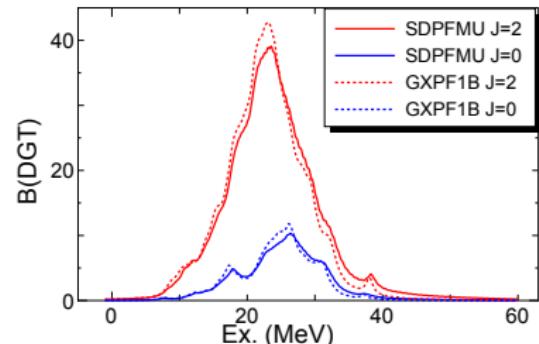
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

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

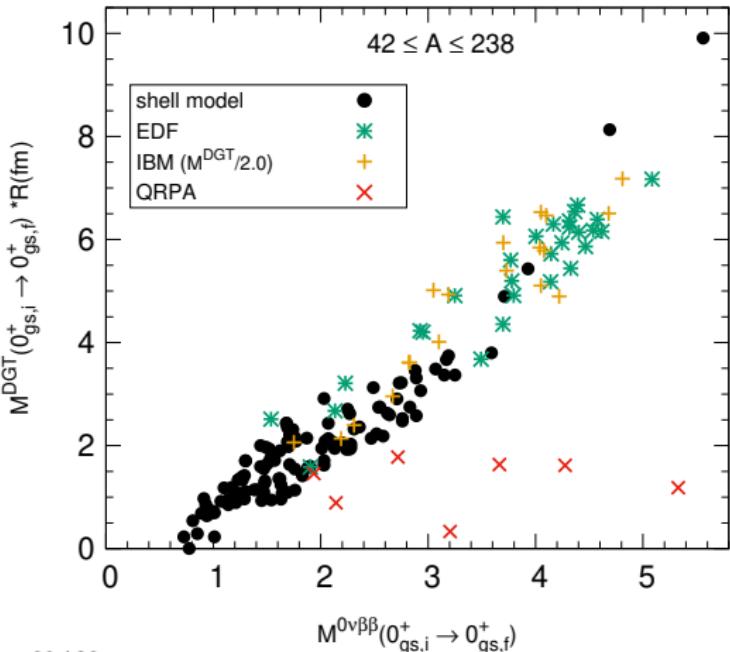
Shimizu, JM, Yako, PRL120 142502 (2018)



$$B(DGT^-; \lambda; i \rightarrow f) = \frac{1}{2J_i + 1} \left| \left\langle ^{48}\text{Ti} \right| \left[\sum_i \sigma_i \tau_i^- \times \sum_j \sigma_j \tau_j^- \right]^{(\lambda)} \left| ^{48}\text{Ca}_{\text{gs}} \right\rangle \right|^2$$

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

Double GT transition to ground state $M^{\text{DGT}} = \langle F_{\text{gs}} | [(\sum_i \sigma_i \tau_i^- \times \sum_j \sigma_j \tau_j^-)^0] | I_{\text{gs}} \rangle|^2$
very good linear correlation with $0\nu\beta\beta$ decay nuclear matrix elements



Double Gamow-Teller correlation with $0\nu\beta\beta$ decay holds across nuclear chart

Shimizu, JM, Yako

PRL120 142502 (2018)

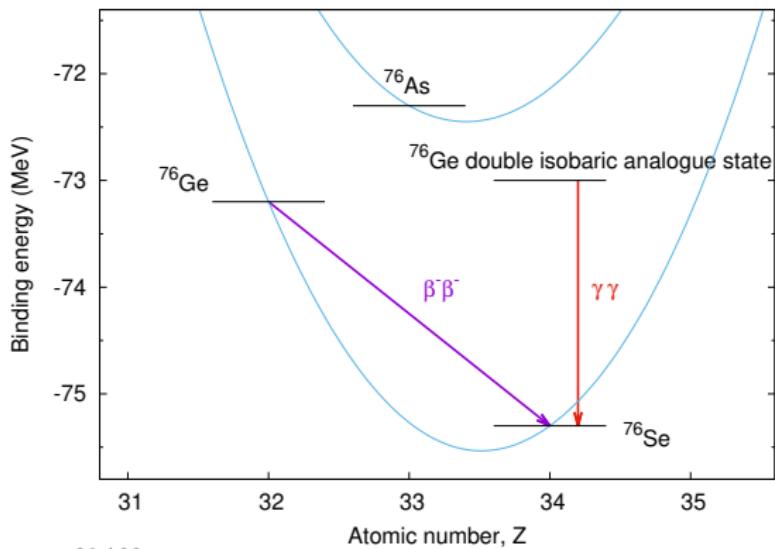
Common to shell model energy-density functionals interacting boson model, disagreement to QRPA

Experiments at RIKEN, INFN Catania may access DGT transitions

Similar $0\nu\beta\beta$ and $\gamma\gamma$ decays?

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

$$M_{M1 M1}^{\gamma\gamma} = \sum_k \frac{\langle 0_f^+ | \sum_n (g_n^l I_n + g_n^s \sigma_n)^{IV} | 1_k^+(IAS) \rangle \langle 1_k^+(IAS) | \sum_m (g_m^l I_m + g_m^s \sigma_m)^{IV} | 0_i^+(DIAS) \rangle}{E_k - (M_i + M_f)/2}$$



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

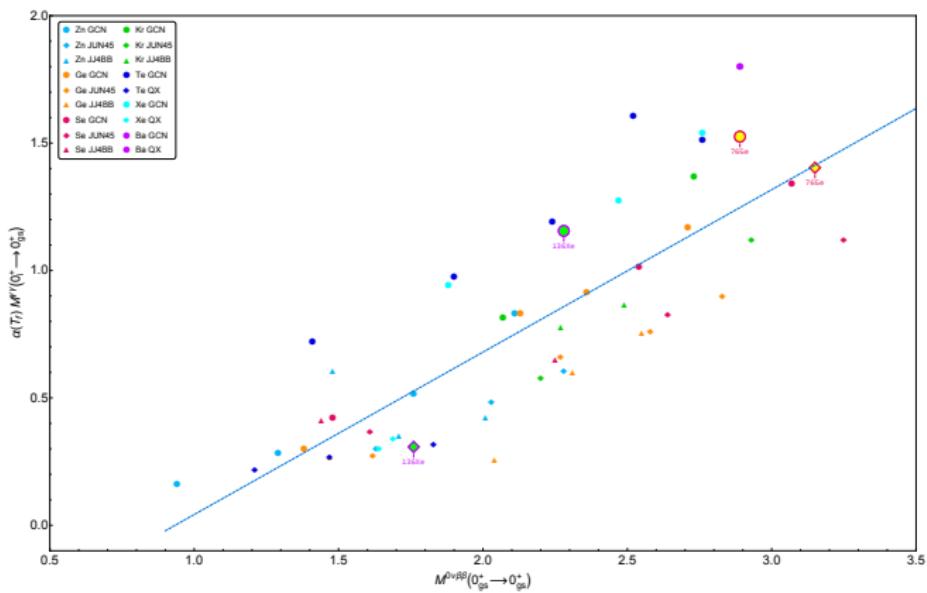
M1 and GT operators similar,
physics of spin operator
M1 also angular momentum

Different energy denominator

Romeo, JM, Peña-Garay, in progress

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

Good linear correlation between $\gamma\gamma$ M1M1 and $0\nu\beta\beta$ decays obtained with nuclear shell model, holds for nuclei with $A \sim 60 - 140$



Includes
 $\beta\beta$ nuclei:
 ^{76}Ge ,
 ^{82}Se ,
 ^{130}Te ,
 ^{136}Xe

Romeo, JM,
Peña-Garay,
in progress

Measurements of $\gamma\gamma$ M1M1 decays could inform $0\nu\beta\beta$ NMEs!

Summary

Nuclear matrix elements key
for the design of next-generation tonne-scale $0\nu\beta\beta$ decay experiments

- Present nuclear matrix element calculations still disagree by factor 2 – 3
- Ab initio calculations solve much of β decay “quenching” problem, ab initio ^{48}Ca NME quite small first extension to heavier $\beta\beta$ nuclei!
- Tests to $2\nu\beta\beta$ lifetimes, electron spectra promising correlations of $0\nu\beta\beta$ with double-GT and $\gamma\gamma$ transitions
- Similar uncertainties in NMEs for BSM exchange of heavy particles

