

Double- β decay: predicting the lifetimes of the slowest decays

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**University of Barcelona
Institute of Cosmos Sciences**

**Zakopane Conference on Nuclear Physics 2026:
“Extremes of the Nuclear Landscape”**

Zakopane, 1st September 2026



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B. Benavente, **D. Castillo**, **D. Frycz**, P. Soriano



TECHNISCHE
UNIVERSITÄT
DARMSTADT

L. Jokiniemi



THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

B. Romeo

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

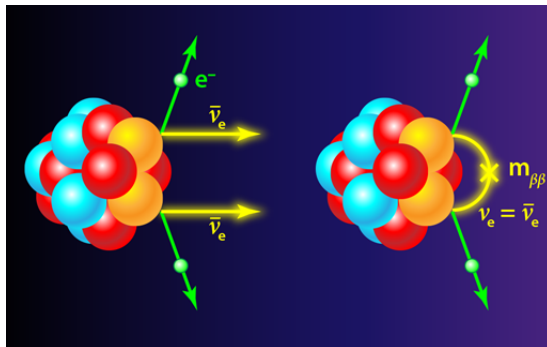
Lepton number is conserved
in all processes observed:

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

Neutral massive particles (Majorana ν 's)
allow lepton number violation:

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

Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)



$$T_{1/2}^{2\nu\beta\beta} \sim 10^{20} \text{ y}$$

$$T_{1/2}^{0\nu\beta\beta} \sim \text{unobserved}$$

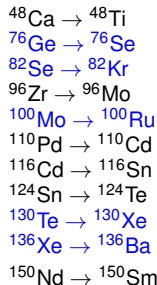
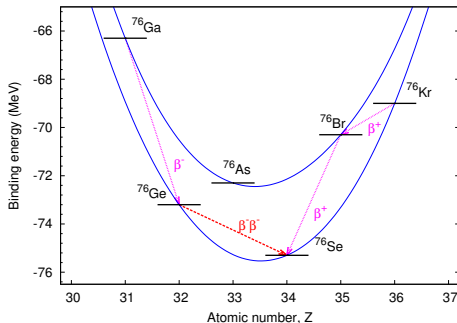
$\beta\beta$ decay

Second order process in the weak interaction

Only observable in nuclei where (much faster) β -decay is forbidden energetically due to nuclear pairing interaction

$$BE(A) = -a_v A + a_s A^{2/3} + a_c \frac{Z(Z-1)}{A^{1/3}} + \frac{(A-2Z)^2}{A} + \begin{cases} -\delta_{\text{pairing}} & \text{N,Z even} \\ 0 & \text{A odd} \\ \delta_{\text{pairing}} & \text{N,Z odd} \end{cases}$$

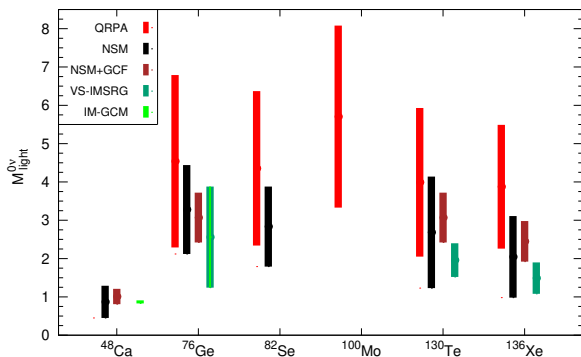
or where β -decay is very suppressed by ΔJ angular momentum change



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

Nuclear matrix element uncertainty impacts expected half-life:

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



Wirth et al.
PRL127 242502 (2021)

Belley et al.
arXiv:2307:15156

Belley et al.
PRL132 182502 (2024)

Jokiniemi et al.
PRC 107 044305 (2023)

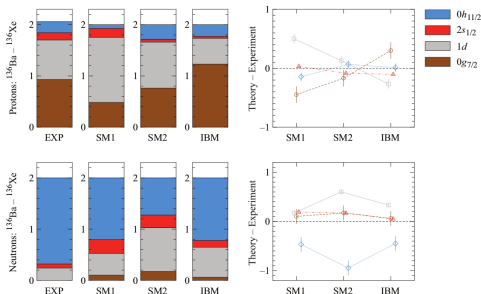
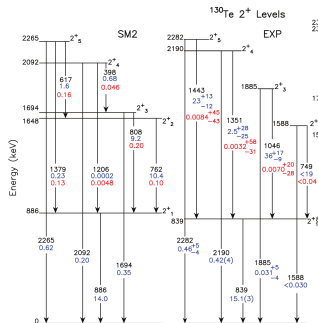
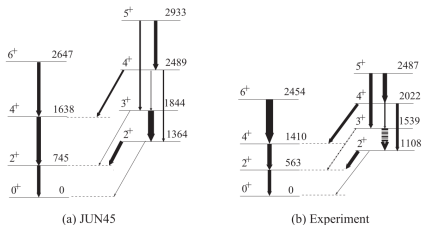
Weiss et al.
PRC106 065501 (2022)

Gómez-Cadenas, Martín-Albo, JM, Mezzeto, Monrabal, Sorel
Riv. Nuovo Cim. 46 619(2023)

- 1 **Tests of nuclear structure** relevant for $0\nu\beta\beta$ decay
- 2 **Correlations** with $0\nu\beta\beta$ decay
- 3 **Predictions of $2\nu\beta\beta$ half-lives**
- 4 **$\gamma\gamma$ decay measurements in $\beta\beta$ nuclei**

Tests of nuclear structure

Good spectroscopy: masses, spectra, transitions, addition/removal...



Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Mukhopadhyay et al. PRC95 014327 (2017)

...

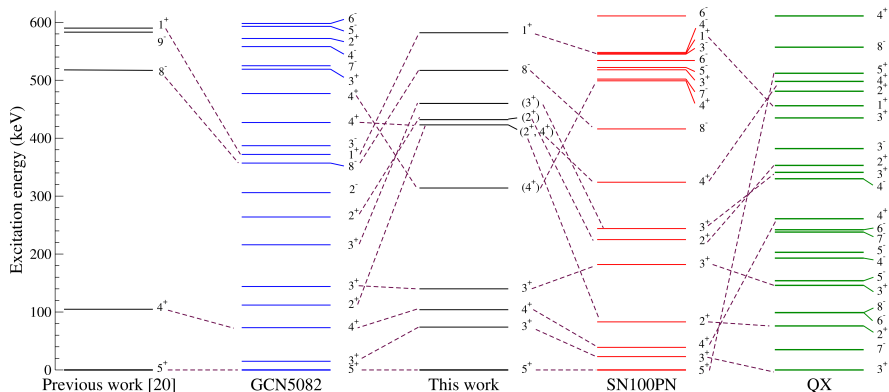
Hicks et al. PRC105 024329 (2022)

...

^{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

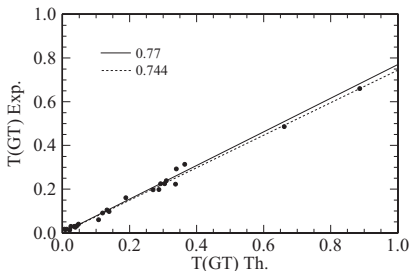
Rebeiro, Triambak et al. PRL131 052501 (2023)



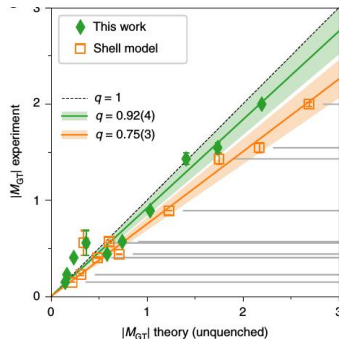
QX systematically smaller ^{136}Xe $0\nu\beta\beta$ -decay nuclear matrix elements

Gamow-Teller β decay: “quenching”

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



Martinez-Pinedo et al. PRC53 2602(1996)



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

Ab initio calculations including meson-exchange currents do not need any “quenching”

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

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

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Correlation analysis: NMEs vs nuclear properties

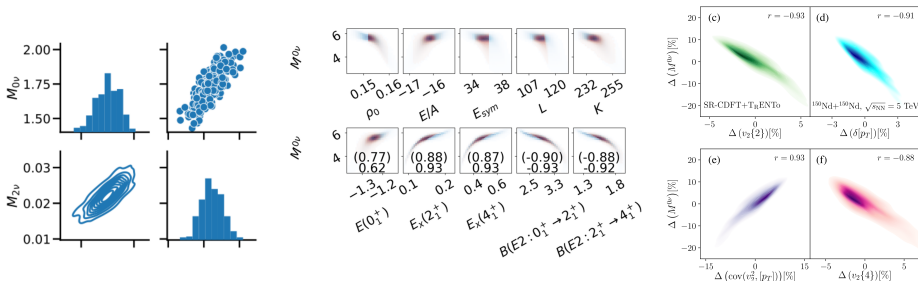
Explore correlation of NMEs with other observables:
two-neutrino $\beta\beta$ decay, observables related to nuclear deformation

Horoi et al. PRC106 054302(2022), 107 045501(2023)

Jokiniemi et al. PRC107 044305 (2023)

Zhang et al. PRC112 L021302 (2025)

Li et al. PRL135 022301 (2025)



Use these observables to calibrate nuclear structure calculations

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

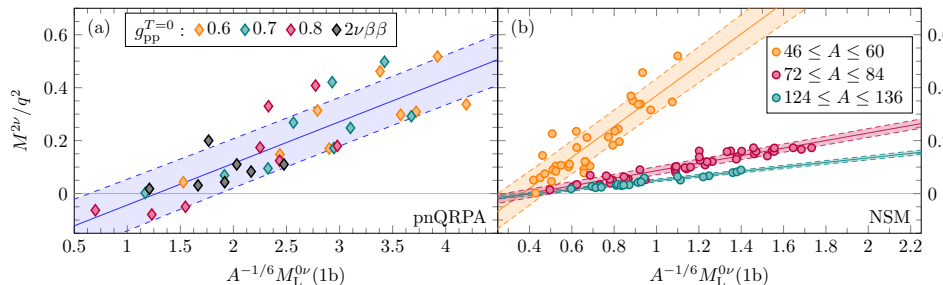
Good correlation between 2ν and 0ν modes of $\beta\beta$ decay
in nuclear shell model (systematic calculations of different nuclei)
and QRPA calculations (decays of $\beta\beta$ emitters with different g_{pp} values)

Similar but not common correlation, depends on mass for shell model

$0\nu\beta\beta - 2\nu\beta\beta$ correlation also observed in other studies

Horoi et al. PRC 106, 054302 (2022), PRC 107, 045501 (2023), arXiv:2605.91657

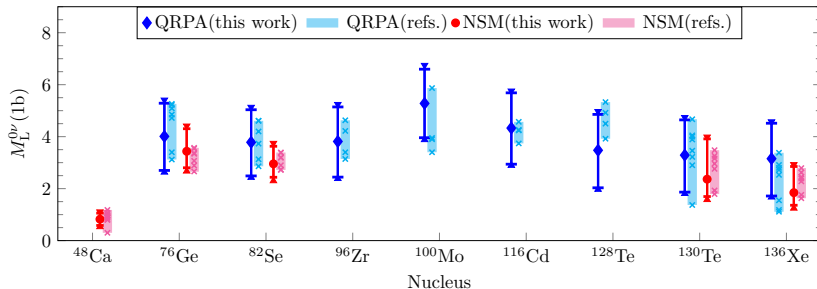
Lian et al. arXiv:2605.19479



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

$0\nu\beta\beta$ NMEs with theoretical uncertainties

NMEs calibrated with data based on correlations of $0\nu\beta\beta$ and other observables



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

NMEs consistent with previous results, take into account model uncertainties

Similar correlations used to obtain theoretical uncertainties:

Zhang et al. PRC112 L021302 (2025), Li et al. PRL135 022301 (2025)

1 Tests of nuclear structure relevant for $0\nu\beta\beta$ decay

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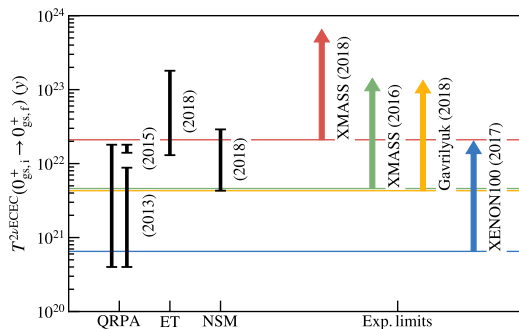
$2\nu\text{EDEC}$ of ^{124}Xe

Two-neutrino $\beta\beta$ predicted for ^{48}Ca before measurement

Caurier, Poves, Zuker, PLB 252 13(1990)

Recent predictions for $2\nu\text{EDEC}$ ^{124}Xe 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

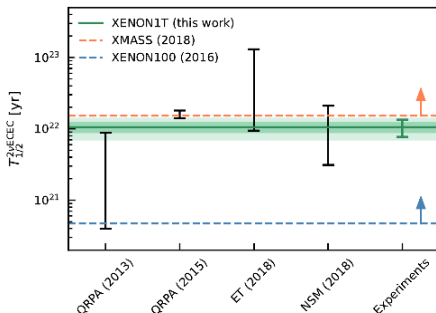
2ν ECEC of ^{124}Xe

Two-neutrino $\beta\beta$ predicted for ^{48}Ca before measurement

Caurier, Poves, Zuker, PLB 252 13(1990)

Recent predictions for 2ν ECEC ^{124}Xe half-life:

shell model error bar largely dominated by “quenching” uncertainty



Shell model, QRPA, Effective theory (ET)
good agreement with XENON1T measurement!

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)

LZ: JPG52 015103(2025)

PANDAX-4T:

JHEP 05 119 (2025)

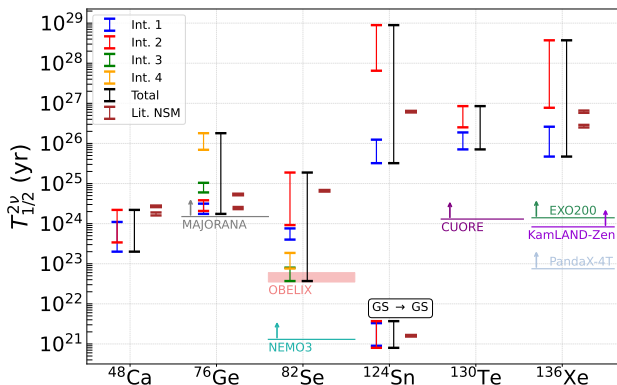
$2\nu\beta\beta$ decay to excited states

Shell-model two-neutrino $\beta\beta$ predictions to excited states

Benavente, Castillo, Frycz, JM, PLB 875 140306 (2026)

including next-to-leading-order corrections (additional matrix elements)
modify half-life $\sim 5\%$, but may be much larger if leading-order cancellations

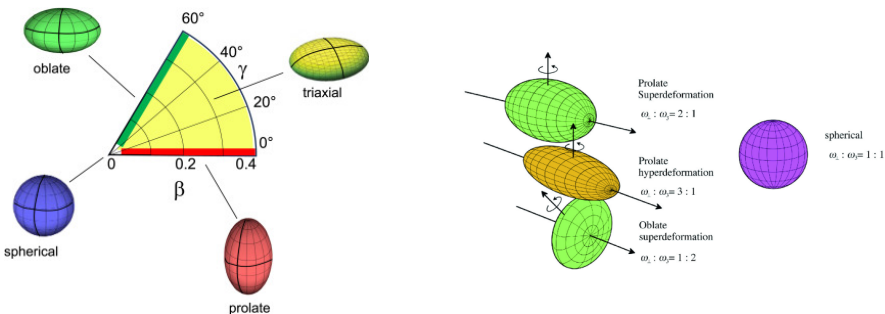
el Morabit et al. JHEP 06 082 (2025)



In general, uncertainty due to nuclear Hamiltonian

Spherical, deformed, superdeformed states

Deformation in nuclei: spherical, oblate, prolate, superdeformed



Leoni, Fornal, Bracco, Tsunoda, Otsuka, Prog. Part. Nucl. Phys. 139 104119 (2024)

Obertelli, Sagawa, Modern Nuclear Physics (2021)

Deformation parameters

$$\beta = \frac{4\pi}{3R_0^2 A} \frac{e_{\text{mass}}}{e} \sqrt{\langle \bar{Q}_{20} \rangle^2 + 2\langle \bar{Q}_{22} \rangle^2}, \quad \gamma = \arctan \left(\frac{\sqrt{2}\langle \bar{Q}_{22} \rangle}{\langle \bar{Q}_{20} \rangle} \right)$$

Shape invariants

Need reference-frame independent (scalar!) quantities
to properly describe deformation: shape invariants

Kumar, Phys. Rev. Lett. 28, 249 (1972)

Cline, Ann. Rev. Part. Nucl. Sci. 36, 683 (1986)

Poves, Nowacki, Alhassid, Phys. Rev. C 101, 054307 (2020)

Couple quadrupole operator
to form scalars:

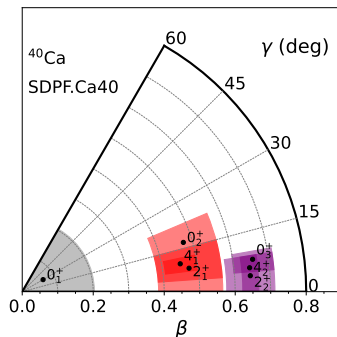
$$\langle [Q_2 \times Q_2]^0 \rangle \propto \beta^2$$

$$\langle [[Q_2 \times Q_2]^2 \times Q_2]^0 \rangle \propto \beta^3 \cos(3\gamma)$$

with uncertainties

$$\frac{\Delta\beta}{\beta} = \frac{\sqrt{\langle Q^4 \rangle - \langle Q^2 \rangle^2}}{2\langle Q^2 \rangle}$$

$$\frac{\Delta\gamma}{\gamma} = \dots$$



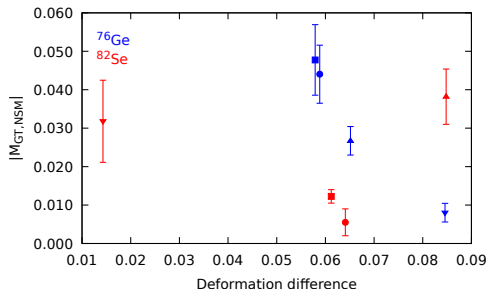
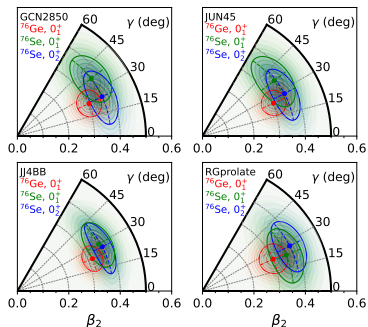
Frycz, Poves, JM, in preparation

Talk by D. Frycz
Wednesday at 19:00

^{76}Ge and ^{76}Se : shape invariants

Shape invariants show that difference in deformation varies quite significantly with the shell-model Hamiltonians used

Castillo, Frycz, Benavente, JM, PLB 875 140306 (2026)



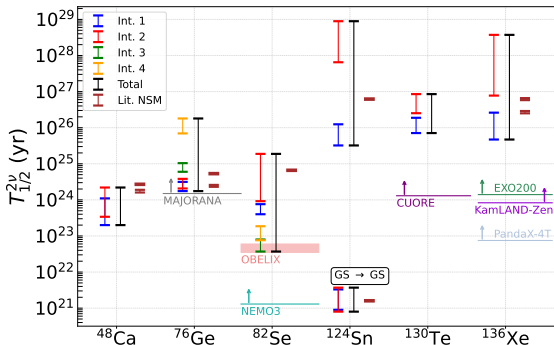
Distance in deformation (β, γ plane) explain big part of different values of the two-neutrino $\beta\beta$ decay nuclear matrix elements

$\Rightarrow$ predict whether $2\nu\beta\beta$ decay in ^{76}Ge to be measured soon or not!

$2\nu\beta\beta$ decay to excited states

Shell-model two-neutrino $\beta\beta$ predictions to excited states
very close to current limit in ^{76}Ge and indication in ^{82}Se

Castillo, Frycz, Benavente, JM, PLB 875 140306 (2026)



Large theoretical uncertainty due to nuclear Hamiltonian:
informed by spectroscopy (deformation): longer half-life for ^{76}Ge preferred

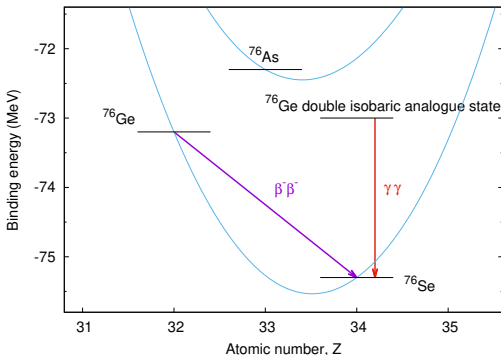
- 1 Tests of nuclear structure relevant for $0\nu\beta\beta$ decay
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$\gamma\gamma$ decay of the DIAS of the initial $\beta\beta$ nucleus

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



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



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

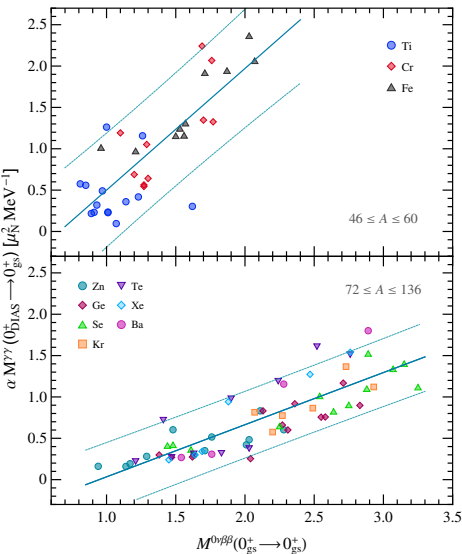
$M1$ and GT operators similar,
physics of spin operator
 $M1$ also angular momentum

Different energy denominator

Romeo, JM, Peña-Garay

PLB 827 136965 (2022)

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



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



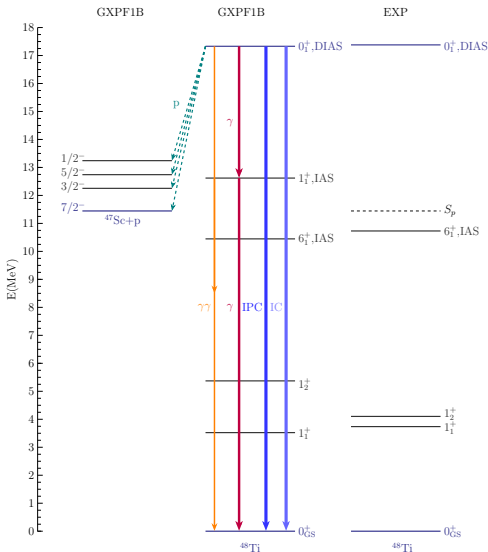
A dependence:
energy denominator
dominant states at higher
energy in heavier nuclei

Overall, study ~ 50 transitions
several nuclear interactions
for each of them

Very suppressed decay
channel: $\Gamma_{\gamma\gamma}/\Gamma_{\text{tot}} \sim 10^{-9}$

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

$\gamma\gamma$ decay from DIAS: competing decays



Competing decay branches
with $\gamma\gamma$ decay:
Th. width $\sim 10^{-7}$ eV

Particle emission
Isospin forbidden!
Th. width ~ 50 eV
(calc. validated in ^{32}S)

Consecutive $E1$ γ decays
Available 1- IAS states?

Consecutive $M1$ γ decays
Th. width ~ 10 eV

$E0$ transitions
Internal conversion / pair creation
Syst. width $\sim 10^{-1}$ eV

Romeo, Stramaccioni, JM, Valiente-Dobón,
PLB 860 139186 (2025)

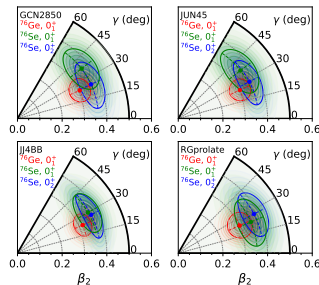
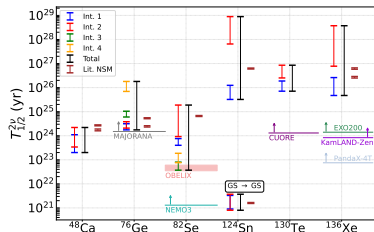
Summary

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

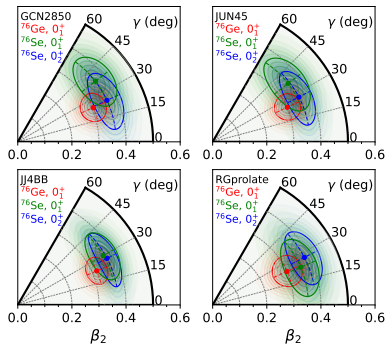
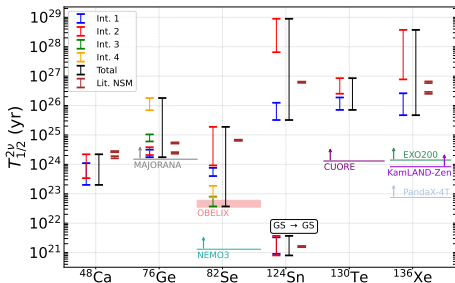
Test quality of NME calculations with nuclear spectroscopy: spectra, EM transitions...

Use other nuclear observables: $2\nu\beta\beta$ to ground and excited states, $M1M1\gamma\gamma$ from DIAS, Double GT... to inform NME values with uncertainties

$2\nu\beta\beta$ to excited state in ^{76}Ge disfavored by nuclear spectroscopy: shape invariants, quadrupole moments

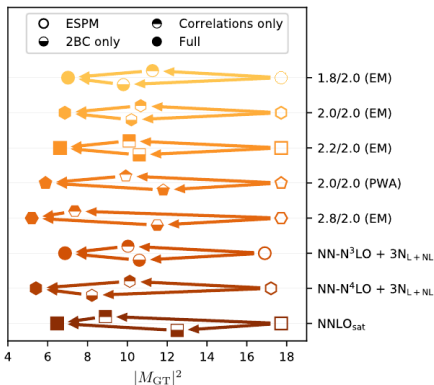


Thank you very much for your attention!



Origin of β -decay “quenching”

Complementary, similar impact of nuclear correlations and meson-exchange currents



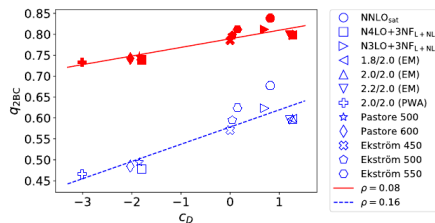
Gysbers et al. Nature Phys. 15 428 (2019)

2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

$$\mathbf{J}_{n,2b}^{\text{eff}} \simeq -\frac{g_A \rho}{f_\pi^2} \tau_n^- \sigma_n \times$$

$$\left[I(\rho) \frac{2c_4 - c_3}{3} - \frac{c_D}{4g_A \Lambda_\chi} - \frac{2g_A \rho}{3f_\pi^2} c_3 \frac{p^2}{m_\pi^2 + p^2} \right]$$



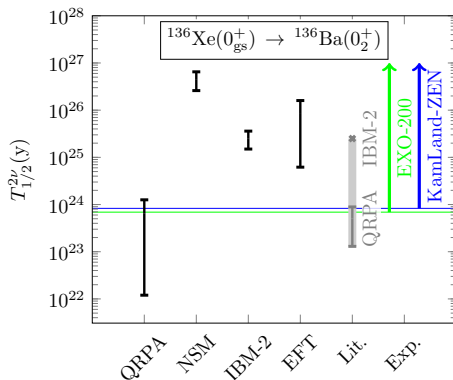
$2\nu\beta\beta$ decay of ^{136}Xe to $^{136}\text{Ba } 0_2^+$

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

EXO-200: Chin. Phys. C 47 (2023)

KamLAND-Zen: Nucl. Phys. A 946 171 (2016)

PANDA-X: JHEP 05 089 (2025)



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

Barea et al.
PRC 91 034304 (2015)

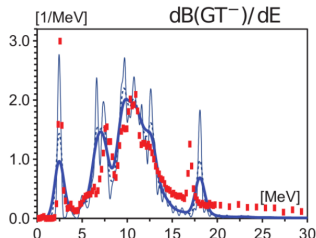
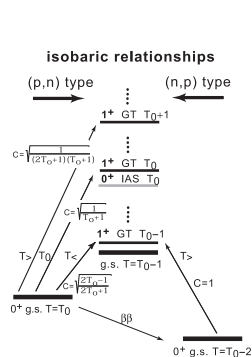
Pirinen, Suhonen
PRC 91, 054309 (2015)

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

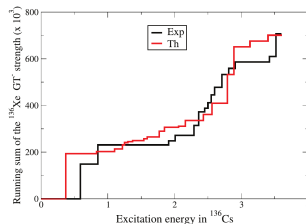
Very good test of theoretical calculations!

Gamow-Teller strengths

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



Iwata et al. JPSCP6 3057 (2015)



Caurier et al. PLB711 62 (2012)

Frekers et al.

NPA916 219 (2013)

$$\frac{d\sigma}{d\Omega}(\theta=0) \propto \sum \sigma_{i\tau}^{\pm}$$

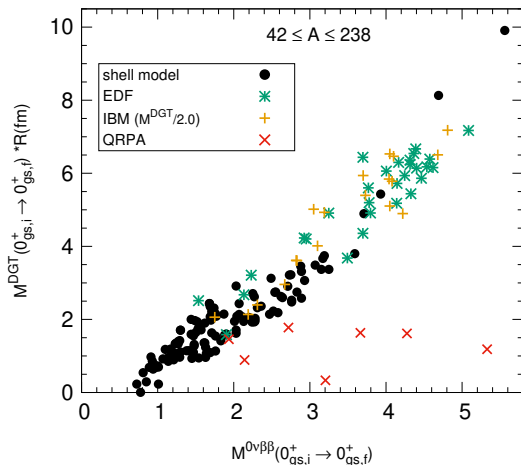
$$\langle 1_f^+ | \sum g_A^{\text{eff}} \sigma_{i\tau_i}^{\pm} | 0_{\text{gs}}^+ \rangle, \quad g_A^{\text{eff}} \sim 0.57 g_A \text{ for } ^{136}\text{Xe}$$

Is it possible to measure high-energy GT strength in heavy $\beta\beta$ emitters?

Is it possible to better measure GT transitions for the β^+ leg?

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
EDF, IBM, QRPA
VS-IMSRG, IM-NCCI

Yao et al. PRC106 014315(2022)

Jokiniemi, JM PRC107 044316(2024)

Lian et al. arXiv:2605.19479

Experiments at
RIKEN, INFN
access DGT transitions

Sakaue et al. PTEP 123D03(2024)

Cavallaro et al.

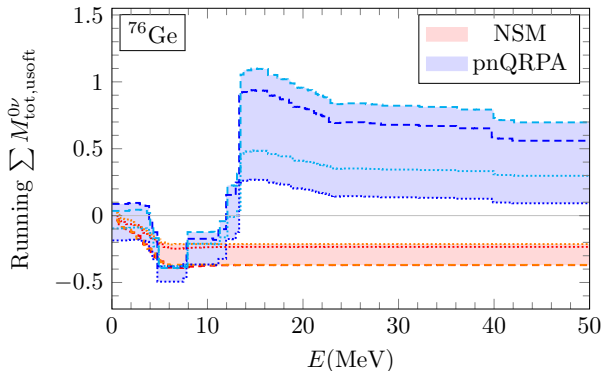
PPNP128 103999 (2023)

Ultrasoft $N^2\text{LO } 0\nu\beta\beta$ nuclear matrix element

Physics of the running sum directly relevant
for the ultrasoft neutrinoless $\beta\beta$ nuclear matrix element as well!

Cirigliano et al. PRC 97 065501 (2018)

Castillo, Jokiniemi, Soriano, JM, PLB 860 139181 (2025)



Determines sign
of this contribution:

negative in shell model
positive in QRPA

Is it possible to measure high-energy GT strength in heavy $\beta\beta$ emitters?

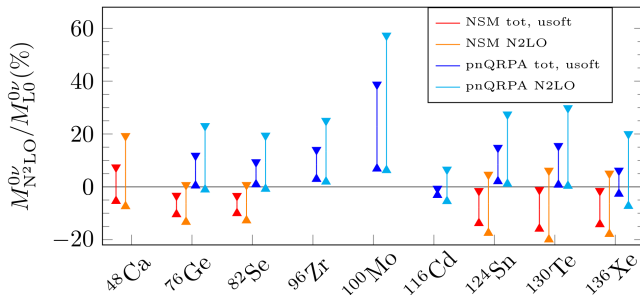
Is it possible to better measure GT transitions for the β^+ leg?

N²LO $0\nu\beta\beta$ nuclear matrix elements

Overall $\sim (10 - 20)\%$ N²LO NME contributions, but larger in few cases:
negative in shell model, while positive in QRPA

Agree with different beyond-closure approximation effects (χ EFT prediction!)

Castillo, Jokiniemi, Soriano, JM, PLB 860 139181 (2025)



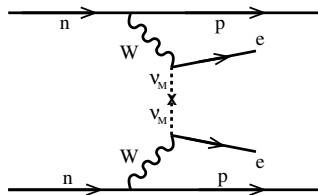
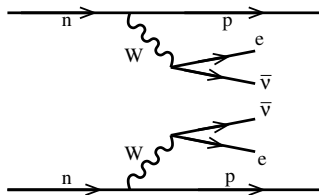
Uncertainties dominated by scale dependence and short-range terms
(phenomenological calculations)

$0\nu\beta\beta$ decay vs $2\nu\beta\beta$ decays

From the theoretical point of view, $0\nu\beta\beta$ and $2\nu\beta\beta$ decays are also different

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

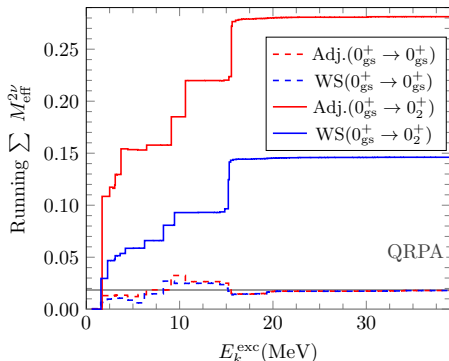
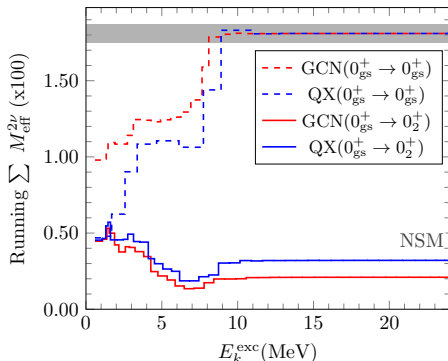
$$M^{0\nu} = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_x H^x(r) \Omega^x | 0_i^+ \rangle$$



- In $2\nu\beta\beta$ decay, the momentum transfer to the leptons is limited by $Q_{\beta\beta}$, while for $0\nu\beta\beta$ decay larger momentum transfers are permitted
- In $0\nu\beta\beta$ decay the Majorana neutrinos annihilate each other which is only possible if neutrinos have mass
- In $0\nu\beta\beta$ decay the Majorana neutrinos are part of the transition operator, via the so-called neutrino potential

$^{136}\text{Xe} \rightarrow ^{136}\text{Ba } 0_2^+$ 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

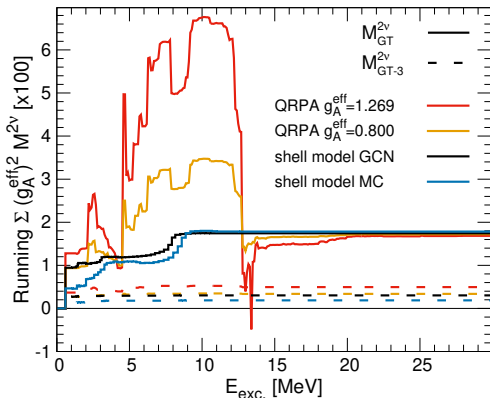
QRPA running sum shows cancellations in decay to excited state

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

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

KamLAND-Zen et al. PRL122 192501 (2019)



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)

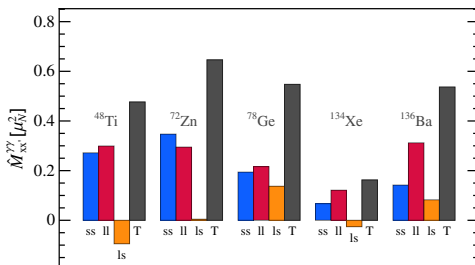
Likewise, $\beta\beta$ decays to excited states stronger predictions of models!

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)

Calculating nuclear matrix elements

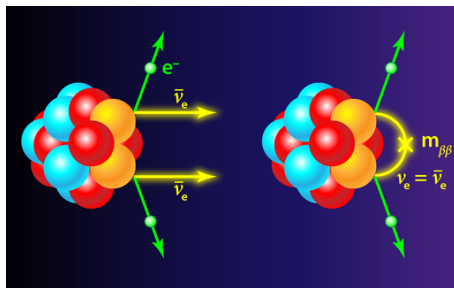
Nuclear matrix elements needed in low-energy new physics searches

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

- **Nuclear structure calculation of the initial and final states:**

Shell model, QRPA, IBM,
Energy-density functional
Ab initio many-body theory
QMC, Coupled-cluster, IMSRG...

- **Lepton-nucleus interaction:**
Hadronic current in nucleus:
phenomenological,
effective theory of QCD



Double-beta decay emitters

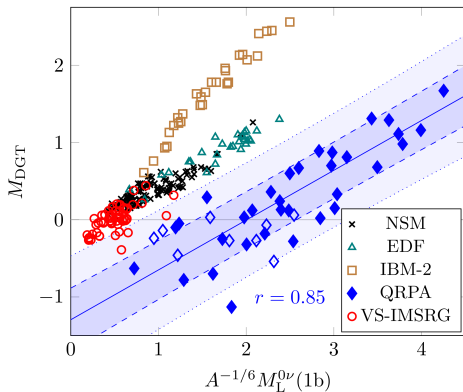
Only decay candidates with $Q_{\beta\beta} > 2$ MeV
experimentally interesting due to extremely long lifetimes

ECEC, $EC\beta^+$ and $\beta^+\beta^+$ also more suppressed

Transition	$T^{2\nu\beta\beta}$ (y)	$Q_{\beta\beta}$ (MeV)	Ab. (%)	
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	$4.4 \cdot 10^{19}$	4.274	0.2	CANDLES
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	$1.7 \cdot 10^{21}$	2.039	8	GERDA, MAJORANA, LEGEND
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	$9.2 \cdot 10^{19}$	2.996	9	SuperNEMO
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	$2.3 \cdot 10^{19}$	3.350	3	
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	$7.1 \cdot 10^{18}$	3.034	10	AMoRE, CUPID
$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$		2.013	12	
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	$2.9 \cdot 10^{19}$	2.802	7	COBRA
$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$		2.288	6	
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	$6.9 \cdot 10^{20}$	2.530	34	CUORE, SNO+
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	$2.2 \cdot 10^{21}$	2.462	9	nEXO, KamLAND-Zen, NEXT, DARWIN
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	$8.2 \cdot 10^{18}$	3.667	6	

Worldwide running and planned experiments on different isotopes

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



Shimizu, JM, Yako, PRL120 142502 (2018)

DGT transition to ground state

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

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

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

Found in:
nuclear shell model
energy-density functional theory
QRPA
ab initio VS-IMSRG (weaker)

Yao et al. PRC106 014315(2022)

Jokiniemi, JM, PRC 107 044316 (2023)

Wang et al. PLB 855 138796 (2024)

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)

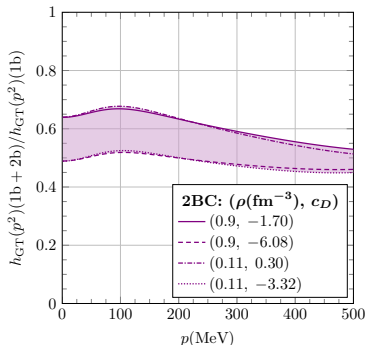
Normal-ordering approximation works remarkably well for β decay ($q = 0$)

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)

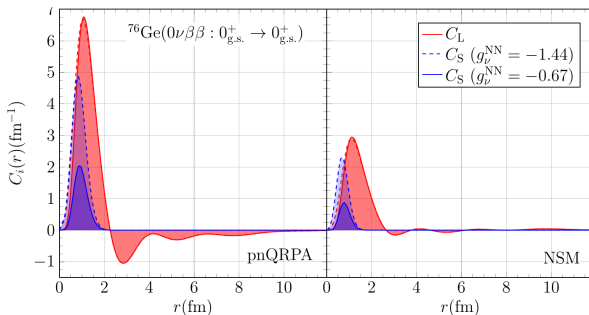
Long and short-range NME in heavy nuclei

Short-range operator contributes to light-neutrino exchange
for RG invariance of two-nucleon decay amplitude: high-energy ν 's

$$T_{1/2}^{-1} = G_{01} g_A^4 (M_{\text{long}}^{0\nu} + M_{\text{short}}^{0\nu})^2 \frac{m_{\beta\beta}^2}{m_e^2}, \quad \text{Cirigliano et al. PRL120 202001(2018)}$$

Relatively stable contribution of new term M_S/M_L :

20% – 50% / 30% – 70% impact of short-range NME in shell model / QRPA
consistent with 43% effect in IM-GCM for ^{48}Ca Wirth et al. PRL127 242502 (2021)



Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021)

Long and short-range NME in heavy nuclei

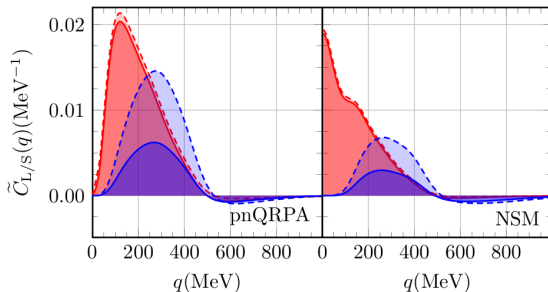
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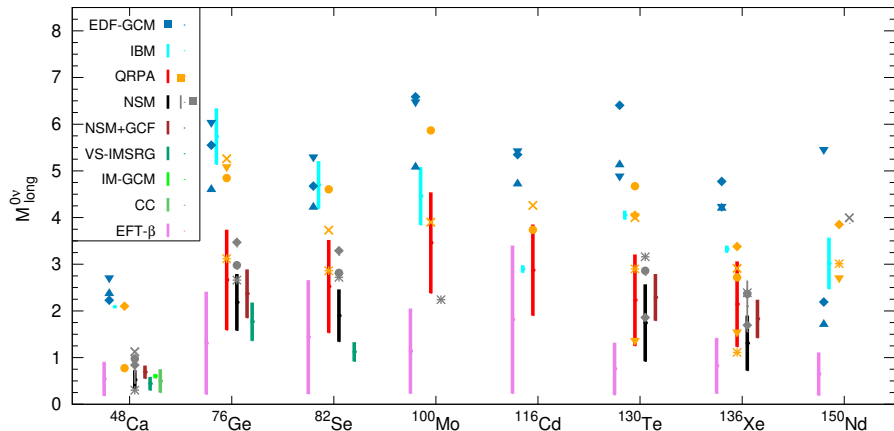
using result from $nn \rightarrow pp + ee$ decay Wirth et al. PRL127 242502 (2021)



Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021)

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

Large difference in nuclear matrix element calculations:



Gómez-Cadenas, Martín-Albo, JM, Mezzeto, Monrabal, Sorel, Riv. Nuovo Cim. 46, 619 (2023)

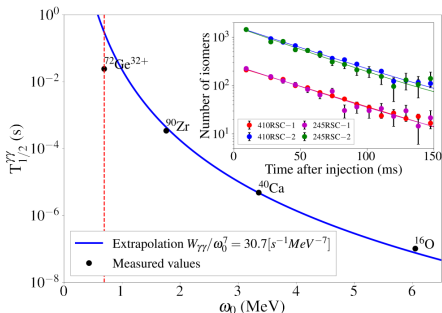
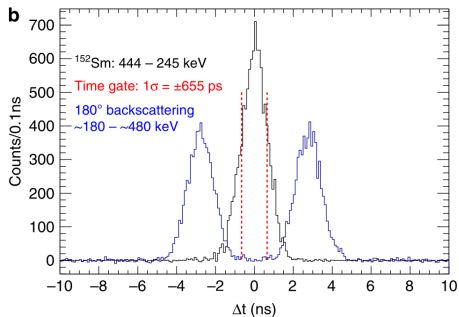
Experimental feasibility of $\gamma\gamma$ decay?

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

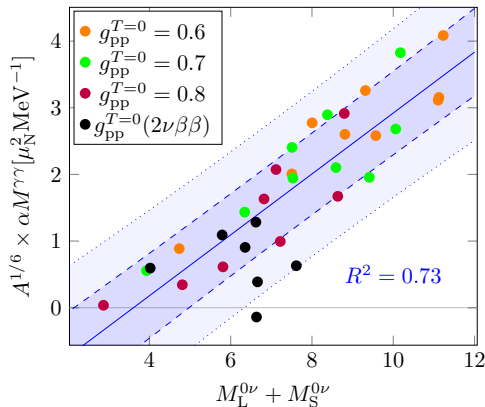
$\gamma\gamma$ decays observed recently in competition with γ decays
Very recent measurement of $\gamma\gamma$ transition in ^{72}Ge

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

Freire-Fernández et al. PRL133 022502 (2024)



Correlation between $M1M1$ and $0\nu\beta\beta$: QRPA



Jokiniemi, JM, PRC107 044316 (2023)

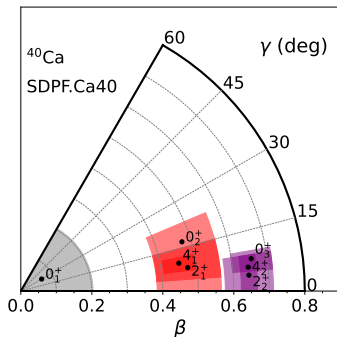
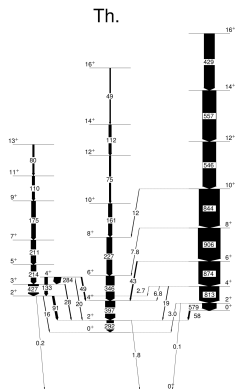
Good correlation between $M1M1$ same-energy photons and QRPA $0\nu\beta\beta$ NMEs valid across the nuclear chart

The correlation is different to the one found by nuclear shell model

Study of dozen $\beta\beta$ nuclei varying the proton-neutron pairing strength

^{40}Ca : spectroscopy + shape invariants

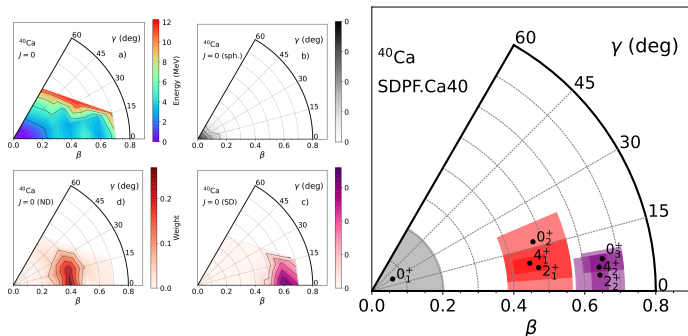
Energies, electromagnetic moments and transitions
combined with shape invariants for all states within a band:
complete picture of shape coexistence

 ^{40}Ca 

Frycz, Poves, JM, in preparation
Caurier, JM, Nowacki, Poves, PRC75 054317(2007)

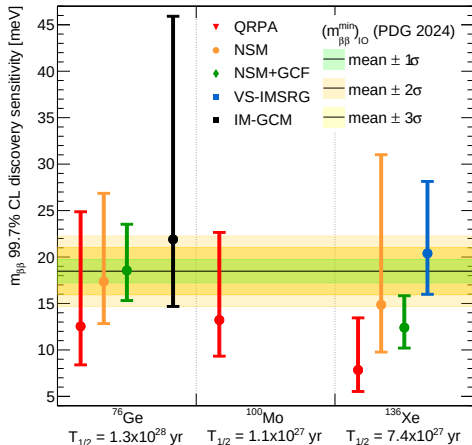
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Energies, electromagnetic moments and transitions
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complete picture of shape coexistence



Frycz, Poves, JM, in preparation
Caurier, JM, Nowacki, Poves, PRC75 054317(2007)

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



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

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!

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

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

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

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

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

Electric dipole moments...

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

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

