Nuclear matrix elements for fundamental symmetries

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Challenges in effective field theory descriptions of nuclei

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UNIVERSITAT DE BARCELONA

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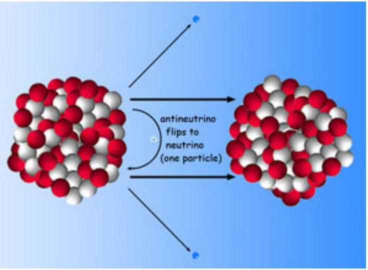
Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

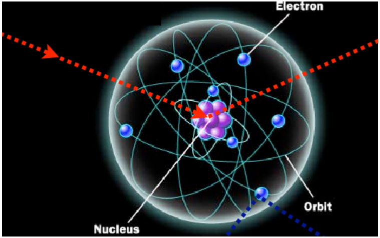
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments



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

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

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



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

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

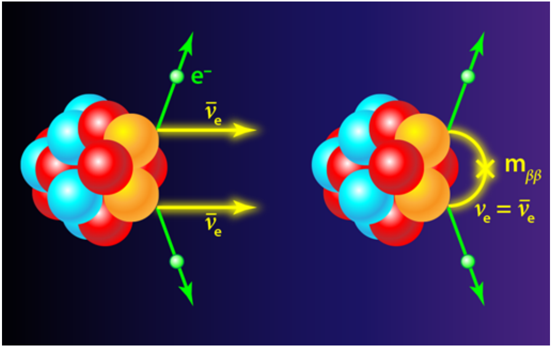
Lepton number is conserved in all processes observed:

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

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

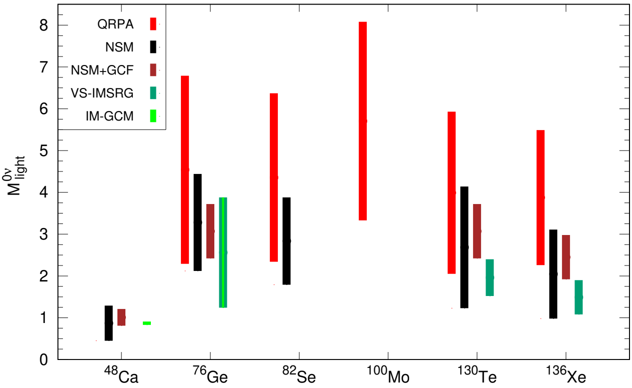
neutrinoless $\beta\beta$ decay
creates two matter particles (electrons)

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



$0\nu\beta\beta$ decay total (long- and short-range) NMEs

Not-so-large difference in nuclear matrix element calculations!
but still theoretical uncertainties are large



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)

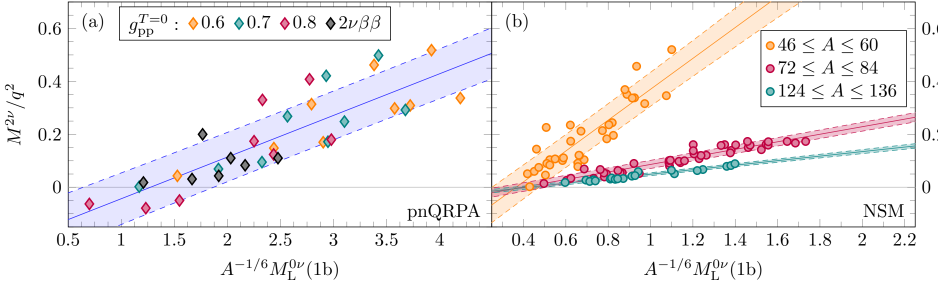
Weiss et al.
PRC106 065501 (2022)

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

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)

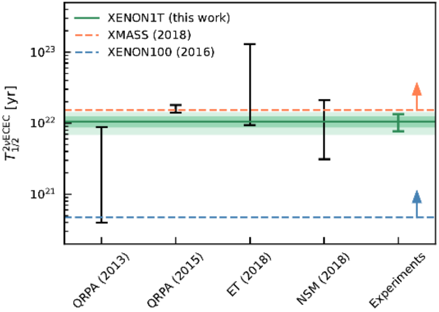
Similar but not common correlation, depends on mass for shell model
$0\nu\beta\beta - 2\nu\beta\beta$ correlation also observed in ^{48}Ca, ^{136}Xe
Horoi et al. PRC 106, 054302 (2022), PRC 107, 045501 (2023)



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

2νECEC of ^{124}Xe

Two-neutrino $\beta\beta$ predicted for ^{48}Ca before measurement
Caurier, Poves, Zuker, PLB 252 13(1990)
Recent predictions for 2νECEC ^{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)

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

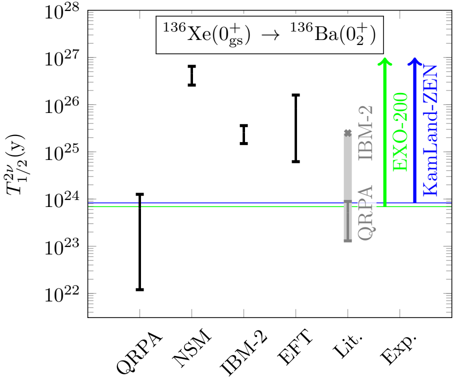
LZ: JPG52 015103(2025)

PANDAX-4T:
JHEP 05 119 (2025)

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

$2\nu\beta\beta$ 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: 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)

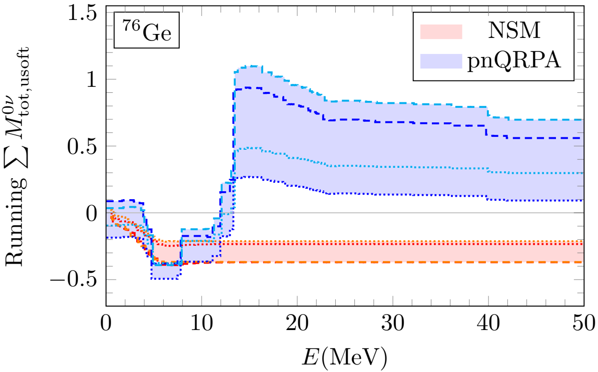
Jokiniemi, Romeo, Brase, Kotila et al.
PLB 838 137689 (2023)

Very good test of theoretical calculations!

Ultrasoft N^{2}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-enegy GT strength in heavy $\beta\beta$ emitters?

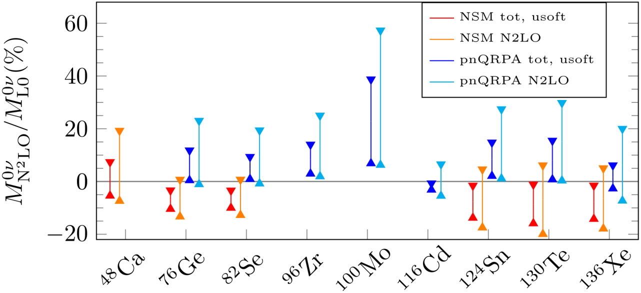
Is it possible to better measure GT transitions for the β^+ leg?

N^{2}LO $0\nu\beta\beta$ nuclear matrix elements

Overall $\sim$ (10 – 20)% N^{2}LO NME contributions, but larger in few cases: negative in shell model, while positive in QRPA

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

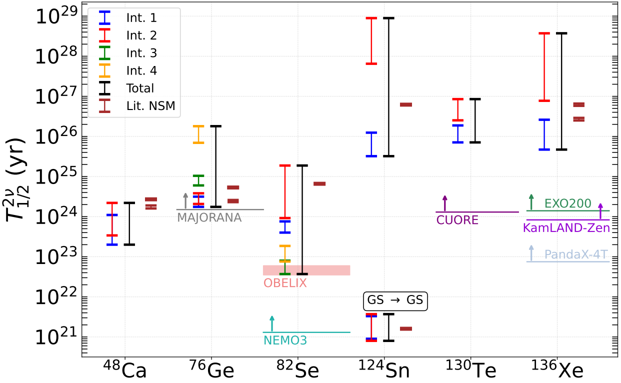
Castillo, Jokiniemi, Soriano, JM, PLB 860 139181 (2025)



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

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

Shell-model two-neutrino $\beta\beta$ predictions to excited states
Benavente, Castillo, Frycz, JM, arXiv:2507.21868
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)

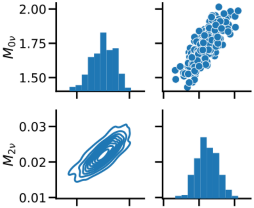


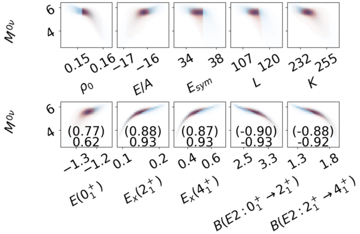
In general, uncertainty due to nuclear Hamiltonian

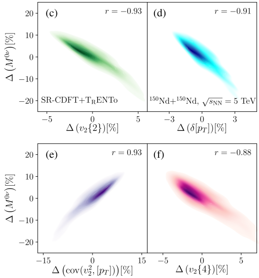
Correlation analysis: NMEs vs nuclear properties

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

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:

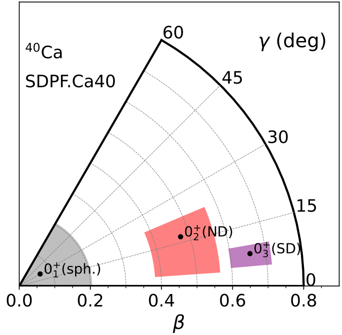
$$\langle [Q_2 \times Q_2]^0 \rangle \propto \beta^2$$

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

with uncertainties

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

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

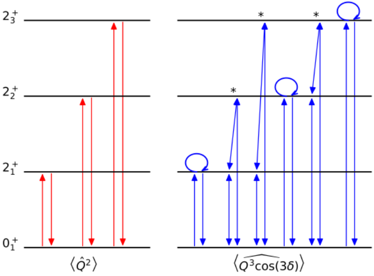


Frycz, Poves, JM, in preparation

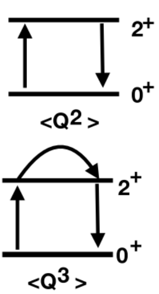
Calculation of shape invariants

Calculation of shape invariants involve sum over all eigenstates connected by the Quadrupole operator
Kumar, Phys. Rev. Lett. 28, 249 (1972)
Cline, Ann. Rev. Part. Nucl. Sci. 36, 683 (1986)

Simpler calculation: only compute “Sum Rule” state (not eigenstate) exhausting the strength of Quadupole operator: $|SR\rangle = Q_2|I\rangle$
Poves, Nowacki, Alhassid Phys. Rev. C 101, 054307 (2020)

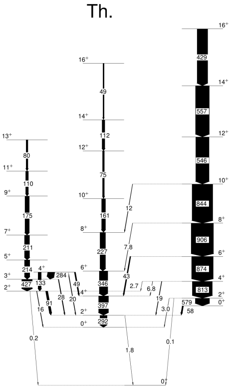


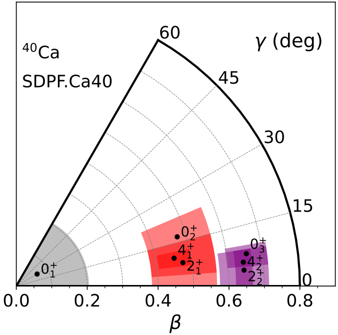
Henderson, PRC102, 054306 (2020)



^{40}Ca: spectroscopy + shape invariants

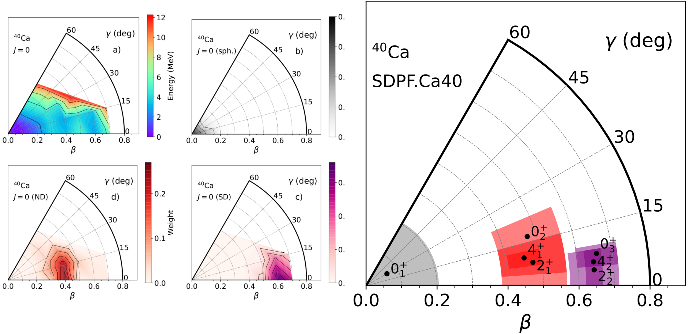
Energies, electromagnetic moments and transitions
combined with shape invariants **for all states within a band**:
complete picture of shape coexistence





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

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

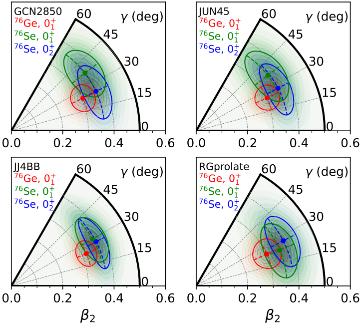


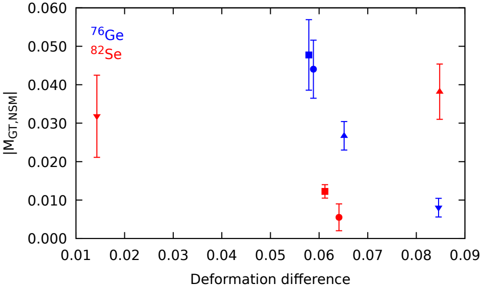
Frycz, Poves, JM, in preparation
Caurier, JM, Nowacki, Poves, PRC75 054317(2007)

^{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, arXiv:2507.21868





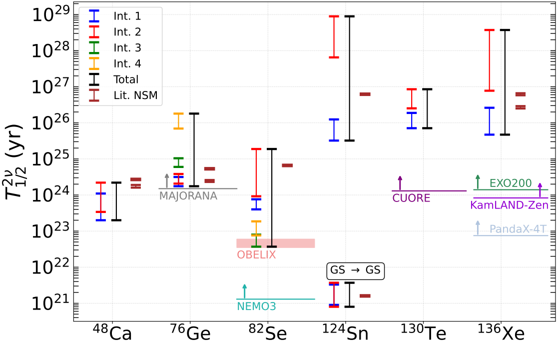
Distance in deformation (β, γ plane) explain big part of different values of the two-neutrino $\beta\beta$ decay nuclear matrix elements

$\Longrightarrow$ 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, arXiv:2507.21868



Large theoretical uncertainty due to nuclear Hamiltonian: informed by spectroscopy (physics of deformation)

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

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

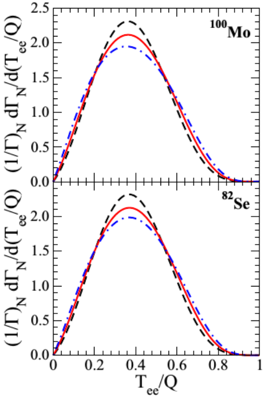
$$(T_{1/2}^{2\nu})^{-1} \simeq g_A^4 \left|(M_{GT}^{2\nu})^2 G_0^{2\nu} + M_{GT}^{2\nu} M_{GT-3}^{2\nu} G_2^{2\nu} + \ldots\right|$$

with

$$M_{GT}^{2\nu} = \sum_j \frac{\langle 0_f^+ | \sum_l \boldsymbol{\sigma}_l \tau_l^- | 1_j^+ \rangle \langle 1_j^+ | \sum_l \boldsymbol{\sigma}_l \tau_l^- | 0_i^+ \rangle}{\Delta},$$

$$M_{GT3}^{2\nu} = \sum_j \frac{4 \langle 0_f^+ | \sum_l \boldsymbol{\sigma}_l \tau_l^- | 1_j^+ \rangle \langle 1_j^+ | \sum_l \boldsymbol{\sigma}_l \tau_l^- | 0_i^+ \rangle}{\Delta^3},$$

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



Šimkovic et al. PRC98 064325 (2018)

Summed electron differential decay rate:

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

Experiments sensitive to ratio of matrix elements: $\xi_{31}^{2\nu} = M_{GT-3}^{2\nu} / M_{GT}^{2\nu}$

Electron spectrum in ^{130}Te $\beta\beta$ decay

CUORE $2\nu\beta\beta$ analysis considers additional terms in $2\nu\beta\beta$ expansion

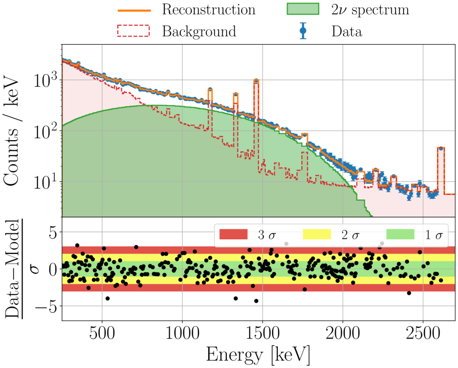
$$(T^{2\nu}_{1/2})^{-1} = g_A^4 \left(M^{(-1)}_{\rm GT}\right)^2 \Delta_0 \left[G_0^{2\nu} + \xi_{31}\frac{\Delta_2}{\Delta_0} G_2^{2\nu} + G_4^{2\nu}\left(\xi_{51}\frac{\Delta_2}{\Delta_0} + \frac{1}{3}\xi_{31}^2\right) + G_{22}^{2\nu}\frac{1}{3}\xi_{31}^2 + \frac{G_M^{2\nu}}{\Delta_0}\right]$$

depending on the ratios of matrix elements:

$$\xi_{31}^{2\nu} = M^{2\nu}_{GT-3}/M^{2\nu}_{GT}$$
$$\xi_{51}^{2\nu} = M^{2\nu}_{GT-5}/M^{2\nu}_{GT}$$

and the next to leading order corrections:

$$\Delta_0 \simeq \Delta_2 \simeq 1$$



CUORE, PRL 135 082501 (2025)

Ratio of $\xi_{31}^{2\nu}$, $\xi_{31}^{2\nu}$ matrix elements

CUORE $2\nu\beta\beta$ fit gives ratios of nuclear matrix elements in tension with the theoretical expectations

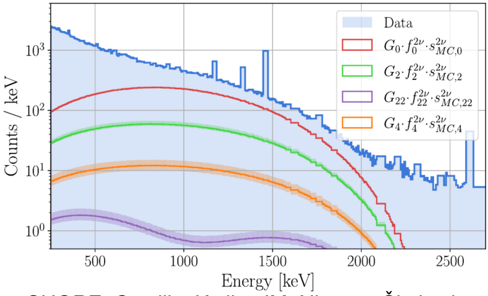
$$\xi_{31}^{2\nu} = 0.01^{+0.31}_{-0.01} \quad \text{vs} \quad 0.12(\text{NSM}) \;/\; 0.20(\text{QRPA})$$
$$\xi_{51}^{2\nu} = 1.46^{+0.33}_{-0.62} \quad \text{vs} \quad 0.03(\text{NSM}) \;/\; 0.05(\text{QRPA})$$

vanishing second-order correction with large third-order correction unexpected according to energy denominators

Similar tension with realistic shell model in ^{100}Mo

Cupid-Mo, PRL131 162501 (2023)

Challenge to describe both half-life and spectrum even with reduced number of nuclear matrix elements!



CUORE, Castillo, Kotila, JM, Nitescu, Šimkovic

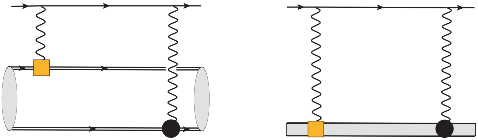
PRL 135 082501 (2025)

Electric dipole moments

EDM's in paramagnetic polar molecules rapid sensitivity improvement

Usually interpreted in terms of electron EDM,
but also sensitive to neutron, proton EDMs via CP-odd electron-nuclear force

If rapid improvement in paramagnetic molecules continues
may compete with current limits in diamagnetic systems (via Schiff moments)



(a) (b)

Dekens et al. arXiv:2510.14933

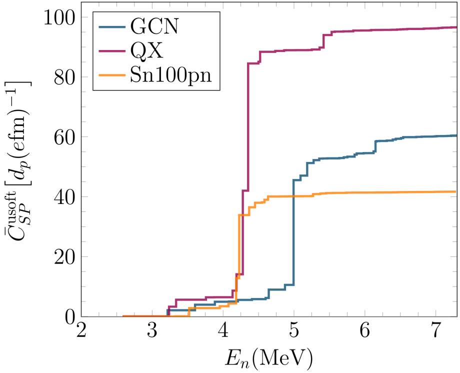
Calculate relevant NMEs for these EDM contributions

Electric dipole moments: ultrasoft contribution

Ultrasoft contribution sensitive to excited excites of nucleus

$$M_{SP}^{\mathrm{usoft}} = \sum_n \frac{\langle h_f | D^{(i)} \vec{\sigma} | n \rangle \cdot \langle n | \mu^{(i)} \vec{\sigma} | h_i \rangle}{\Delta_n} \times \left(1 + 3 \ln \frac{4\Delta_n^2}{m_e^2} \right)$$

Dekens et al. arXiv: 2510.14933



Sizeable sensitivity on nuclear structure, nuclear Hamiltonian used

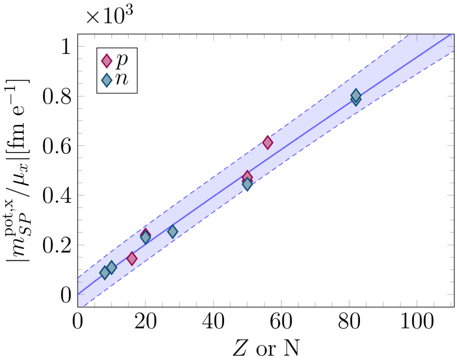
Related to utrasoft NMEs in $\beta\beta$ decays: likely similar uncertainties

Electric dipole moments: potential contribution

Potential contribution: almost full coherence of $S=0$ pairs:
nuclear matrix elements dictated by proton and neutron number

$$V(\vec{r}) = -\frac{e^4 m_e}{18\pi m_N} \sum_{i\neq j} \mu^{(i)} D^{(j)} \times |\vec{r}| \left[\sigma^{(i)} \cdot \sigma^{(j)} + \frac{1}{16} S^{(ij)}(r)\right]$$

Dekens et al. arXiv: 2510.14933



Dominant term due to coherence:
overall, estimated limits from paramagnetic molecules $2-3$ orders of magnitude weaker than proton EDM from ^{199}Hg and the neutron EDM.

Small relevance of radial dependence: dominated by short distances

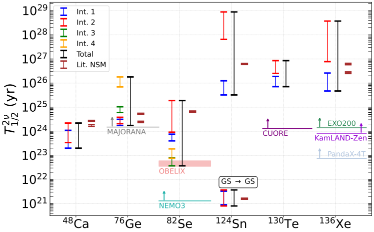
Summary

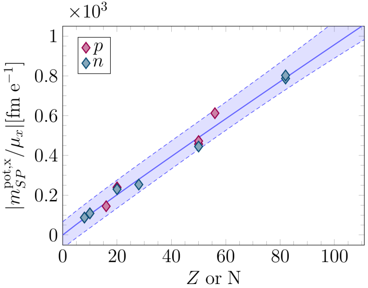
Calculations of $0\nu\beta\beta$, EDM NMEs challenge nuclear many-body methods, experiments demand reliable NMEs

Will $2\nu\beta\beta$ to excited state in ^{76}Ge be measured soon by LEGEND?
Disfavored by Hamiltonian with best nuclear spectroscopy, relevant for $\beta\beta$ decay

Tension between predicted and calculated $2\nu\beta\beta$ electron spectra

EDM NMEs for paramagnetic systems dominated by coherence of $S = 0$ pairs





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Program Overview

Recommended Values for Neutrinoless Double-Beta Decay Nuclear Matrix Elements

June 29, 2026 - July 24, 2026

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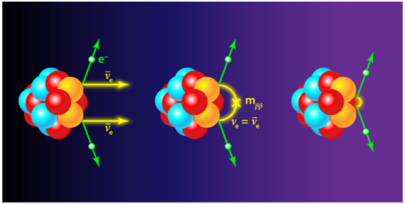

APS / Alan Stonebraker

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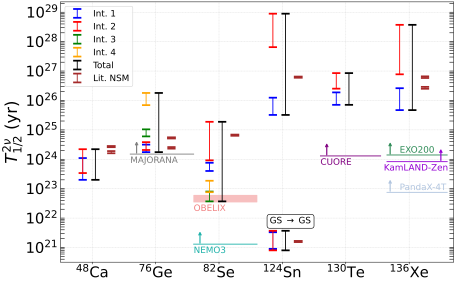
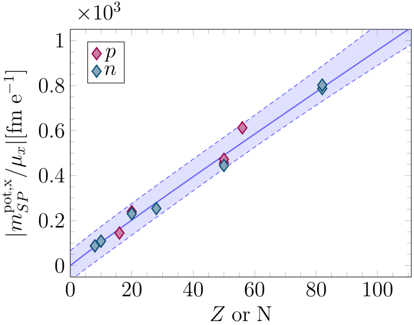
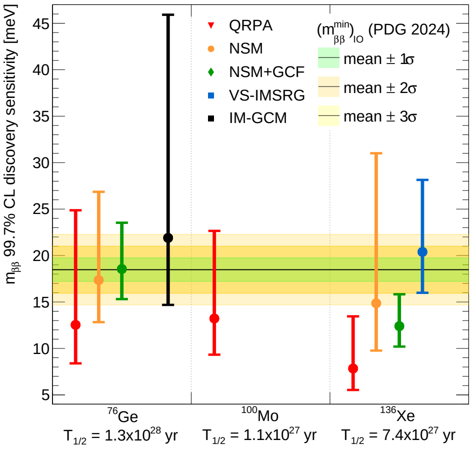
Thank you very much for your attention!

Feel free to ask any questions!





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



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

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

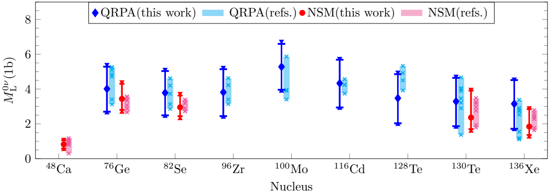
Nuclear matrix element theoretical uncertainty critical to anticipate $m_{\beta\beta}$ sensitivity of future experiments

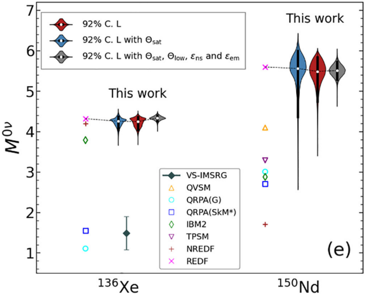
Current uncertainty in $m_{\beta\beta}$ prevents to foresee if next-generation experiments will fully cover parameter space of “inverted” neutrino mass hierarchy

Uncertainty needs to be reduced!

$0\nu\beta\beta$ NMEs: estimate theoretical uncertainties

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





NMEs consistent with previous results, but also take into account model uncertainties

Jokiniemi et al. PRC107 044305 (2023)

Zhang et al. PRC112 L021302 (2025)

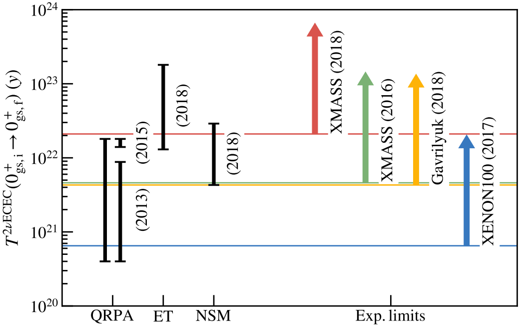
2νECEC of ^{124}Xe

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

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

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

shell model error bar largely dominated by “quenching” uncertainty



Suhonen
JPG 40 075102 (2013)

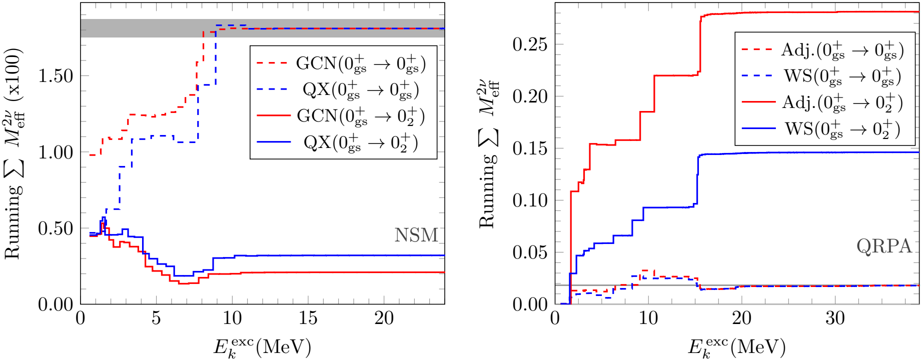
Pirinen, Suhonen
PRC 91, 054309 (2015)

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

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

^{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

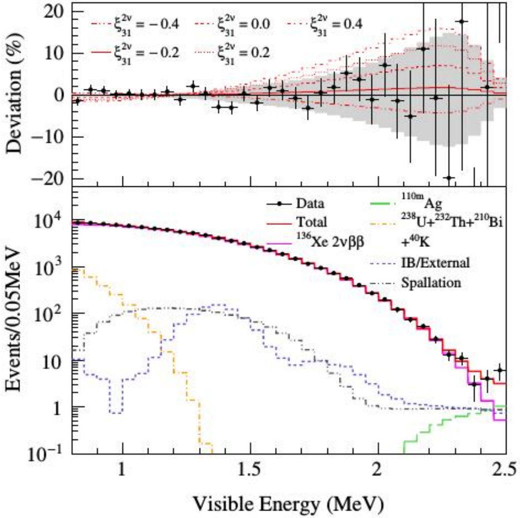
QRPA running sum shows cancellations in decay to excited state

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

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

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

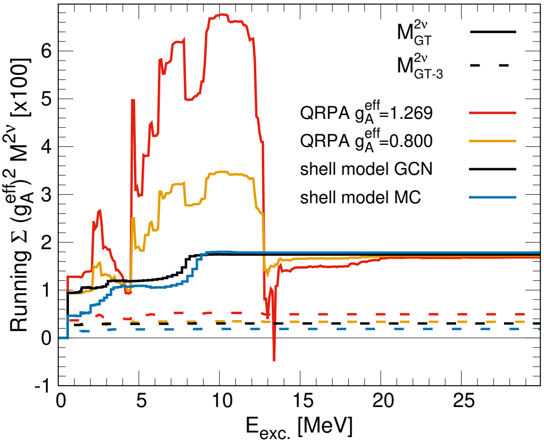
KamLAND-Zen $2\nu\beta\beta$ analysis excludes larger values of $\xi_{31}^{2\nu}$



KamLAND-Zen, PRL122 192501 (2019)

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

Measurements of $\beta\beta$ decay spectra can distinguish calculations with very 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)

KamLAND-Zen
JM, Dvornicky, Šimkovic
PRL122 192501 (2019)

Two-neutrino $\beta\beta$ decay calculations

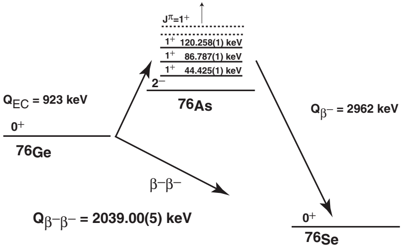
$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \sigma_n \tau_n^- | 1_k^+ \rangle \langle 1_k^+ | \sum_m \sigma_m \tau_m^- | 0_i^+ \rangle}{E_k - (M_i + M_f)/2}$$

Shell Model $2\nu\beta\beta$ decay calculations in good agreement to experiment

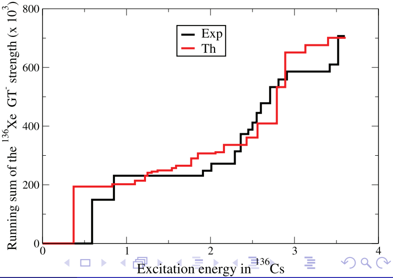
GT quenching is needed

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.

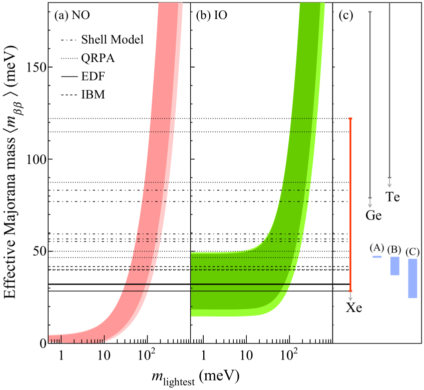
	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
$^{48}Ca \to ^{48}Ti$	0.047 ± 0.003	0.74	0.047	kb3
$^{48}Ca \to ^{48}Ti$	0.047 ± 0.003	0.74	0.048	kb3g
$^{48}Ca \to ^{48}Ti$	0.047 ± 0.003	0.74	0.065	gxpf1
$^{76}Ge \to ^{76}Se$	0.140 ± 0.005	0.60	0.116	gcn28:50
$^{76}Ge \to ^{76}Se$	0.140 ± 0.005	0.60	0.120	jun45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



Gamow-Teller Strengths
(β^- leg of the $\beta\beta$ decay) well reproduced



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



KamLAND-Zen, PRL135 262501 (2025)

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

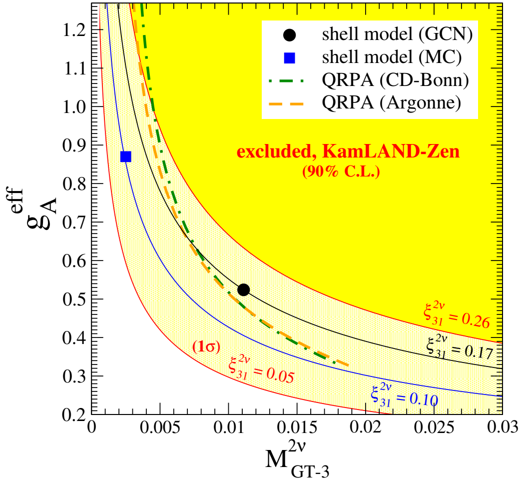
Nuclear matrix element
theoretical uncertainty critical
to anticipate $m_{\beta\beta}$ sensitivity
of future experiments

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!

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 ("queching")

$\xi_{31}^{2\nu}$ 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)