Test and predict neutrinoless $\beta\beta$ decay with other observables

Javier Menéndez

University of Barcelona
Institute of Cosmos Sciences

Second Workshop on
“Neutrinoless double beta decay and related topics”

20^{th} May 2023

UNIVERSITAT DE BARCELONA

MINISTERIO DE CIENCIA E INNOVACIÓN

UNIÓN EUROPEA
Fondo Social Europeo
El FSE invierte en tu futuro

AGENCIA ESTATAL DE INVESTIGACIÓN

ICCUB

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

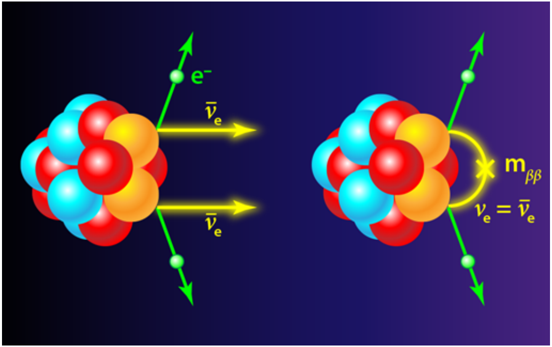
Lepton number is conserved
in all processes observed:

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

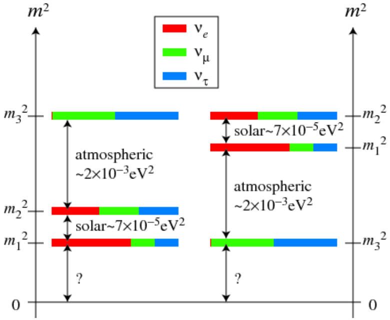
Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. in press, arXiv:2202.01787

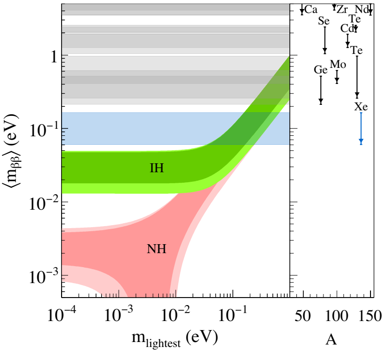


Next generation experiments: inverted hierarchy

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

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

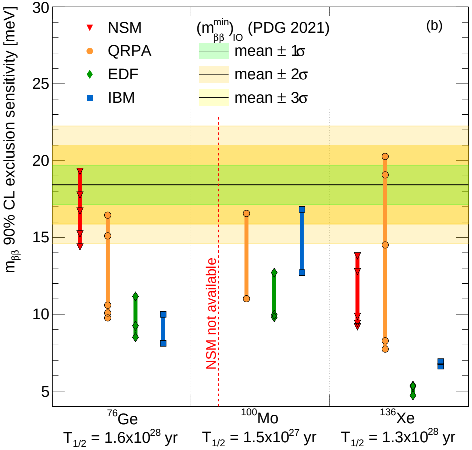




KamLAND-Zen, PRL117 082503(2016)

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 for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

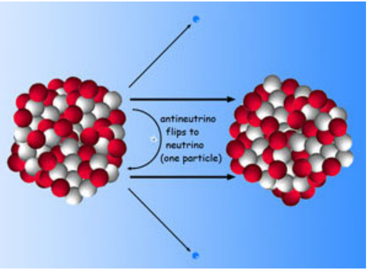
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

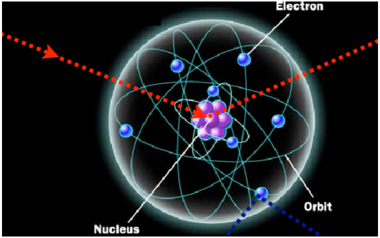
$$0\nu\beta\beta: \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

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

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

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



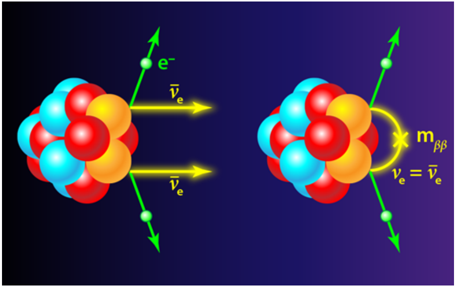


Nuclear matrix elements

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

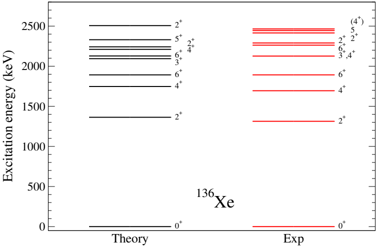
$$\langle \text{Final} \,|\mathcal{L}_{\text{leptons}-\text{nucleons}}|\, \text{Initial} \rangle = \langle \text{Final} \,|\int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial} \rangle$$

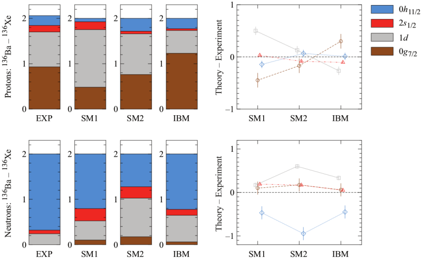
- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  QMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD

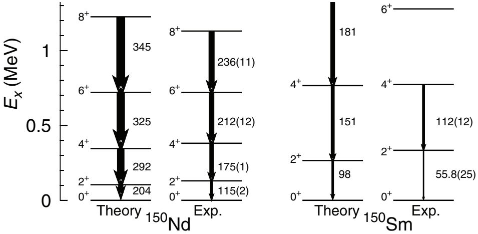


Tests of nuclear structure

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)

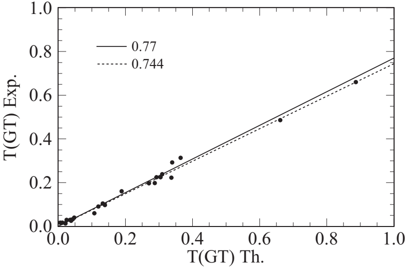
Rodríguez et al. PRL105 252503 (2010)

...

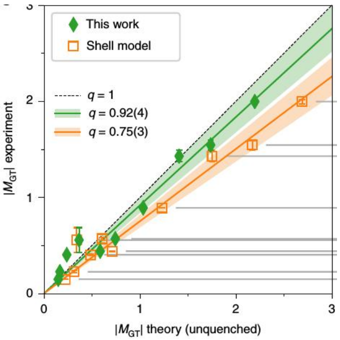
Vietze et al. PRD91 043520 (2015)

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"

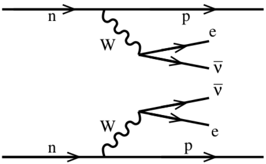
Ab initio calculations including
meson-exchange currents
and additional nuclear correlations
do not need any "quenching"

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)



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

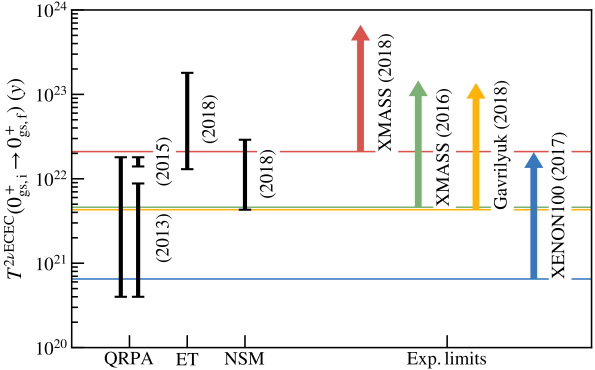
Table 2
The ISM predictions for the matrix element of several 2ν double beta decays (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
^{48}Ca $\to$ ^{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

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

Two-neutrino ECEC of ^{124}Xe

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



Suhonen
JPG 40 075102 (2013)

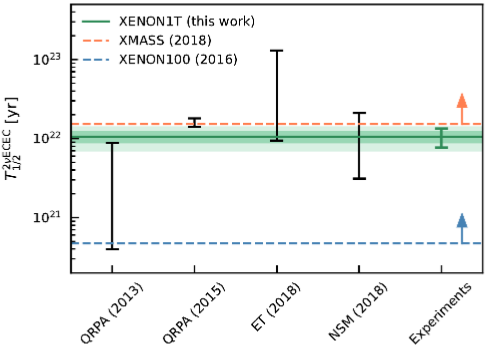
Pirinen, Suhonen
PRC 91, 054309 (2015)

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:
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)

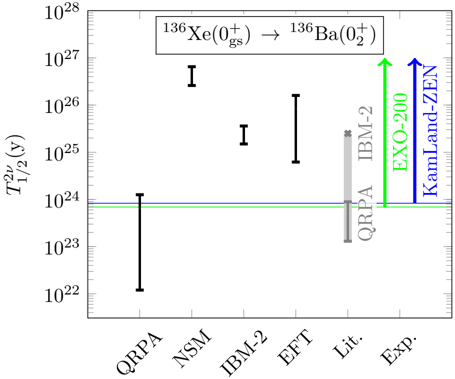
XENON1T
Nature 568 532 (2019)
PRC106, 024328 (2022)

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

$2\nu\beta\beta$ 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)

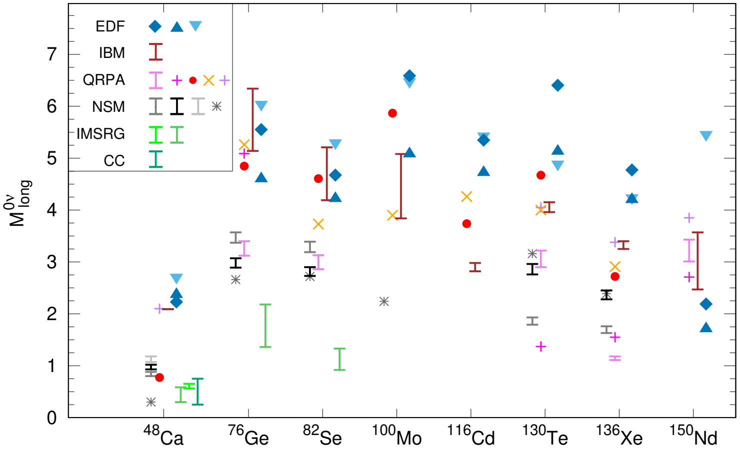
Pirinen, Suhonen
PRC 91, 054309 (2015)

Jokiniemi, Romeo, Brase, Kotila et al.
PLB in press, arXiv:2211.03764

Very good test of theoretical calculations!

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

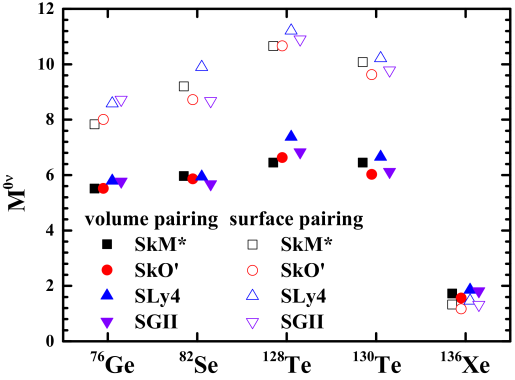
Large difference in nuclear matrix element calculations: factor ~ 3



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

Skyrme+QRPA calculations: pairing sensitivity

Exploring volume/surface pairing in Skyrme QRPA calculations
suggests possible larger values of NMEs
for wide variety of Skyrme functionals considered



Lv et al. arXiv:2302.04423

IM-GCM $0\nu\beta\beta$ 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 IM-GCM calculation reproduces EM transitions in ^{48}Ti

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

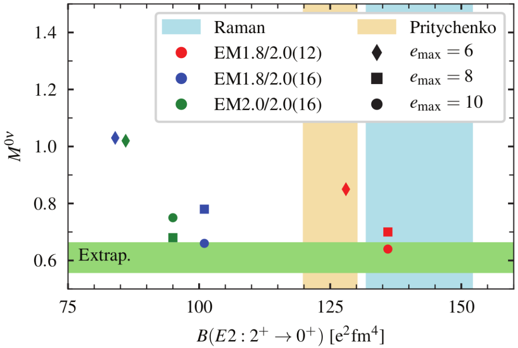
Yao et al.

PRL 124 232501 (2020)

Consistent with coupled cluster NME

Novario et al.

PRL 126 182502 (2021)



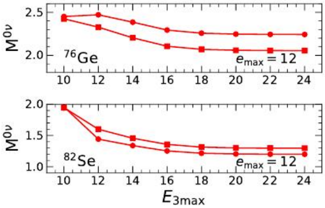
VS-IMSRG $0\nu\beta\beta$ NME for ^{76}Ge, ^{82}Se

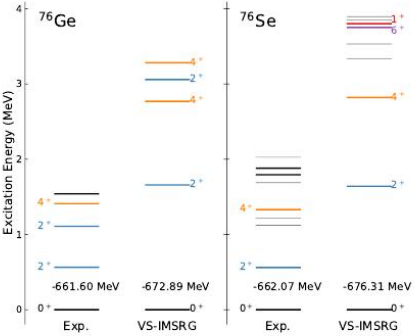
VS-IMSRG reaches ^{76}Ge one of the targets used in most advanced experiments (GERDA, MAJORANA)

VS-IMSRG NME converged in 3N matrix elements included
Miyagi et al.
PRC105 014302 (2022)

Excitation spectra too spread quadrupole correlations not properly captured?

NME $\sim 20\%/50\%$ smaller than nuclear shell model
Belley et al.
PRL126 042502 (2021)





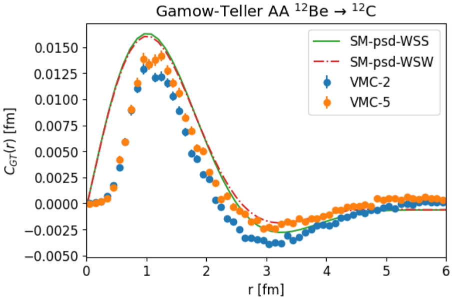
Shell model vs quantum Monte Carlo: correlations

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)

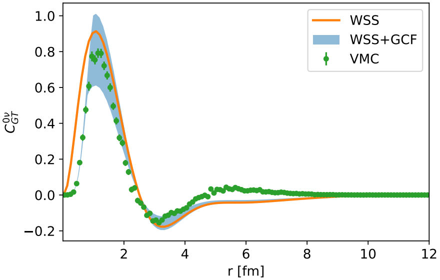
Separation of scales: wf, transition density factorize for two nearby nucleons

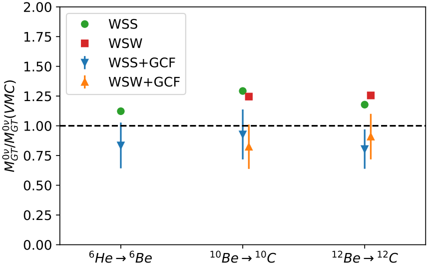
$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_\alpha \varphi^\alpha(\boldsymbol{r}_{ij}) A^\alpha(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j}), \quad \rho_{GT}(r) \xrightarrow[r\to 0]{} -3|\varphi^0(r)|^2 C^0_{pp,nn}(f,i)$$

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



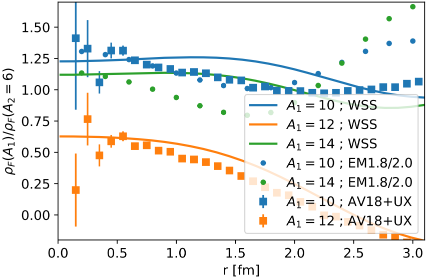


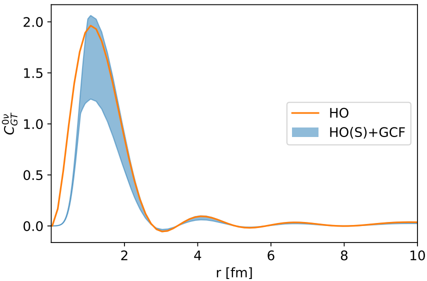
GCF: model independence of ratios

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:



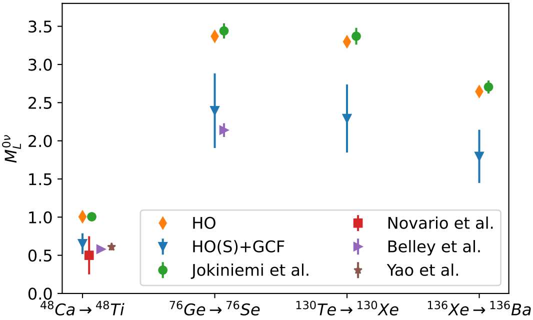


Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

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

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

Cirigliano et al. PRL120 202001(2018)

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

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

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

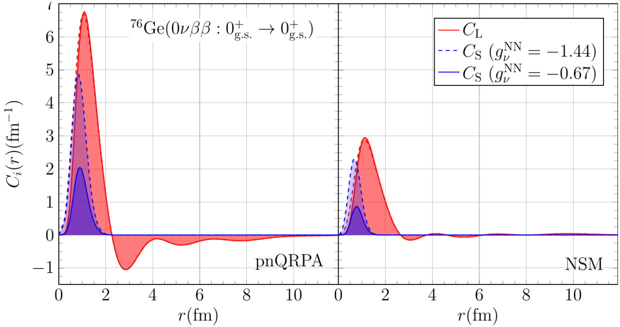
Lattice QCD calculations can obtain value of g_ν^{NN}
Davoudi, Kadam, Phys. Rev. Lett. 126, 152003 (2021), PRD105 094502('22)
or match $nn \rightarrow pp + ee$ amplitude calculated with approximate QCD methods
Cirigliano et al. PRL126 172002 (2021), JHEP 05 289 (2021)
or charge-independence breaking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

Long and short-range NME in heavy nuclei

Relatively stable contribution of new term M_S/M_L:

20% – 50% impact of short-range NME in shell model
30% – 70% impact of short-range NME in QRPA

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)



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

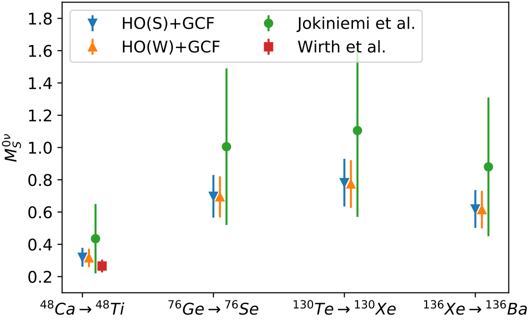
Uncertainty dominated by coupling g_ν^{NN}

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 $g_\nu^{\rm NN}$ 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)

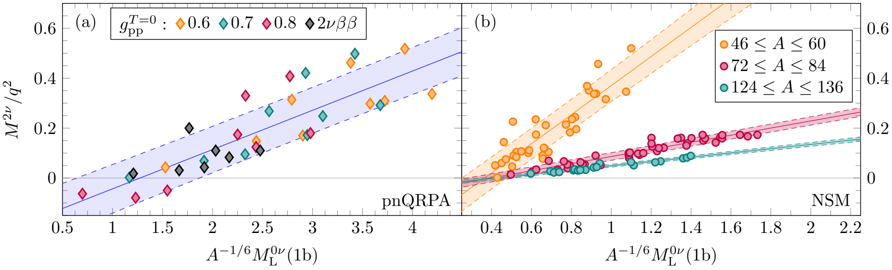


Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

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 Horoi et al. arXiv:2203.10577



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

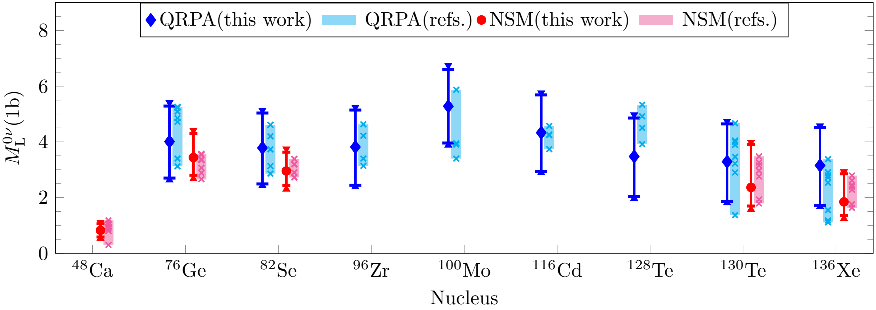
Use $2\nu\beta\beta$ data to predict $0\nu\beta\beta$ NMEs!

$0\nu\beta\beta$ 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

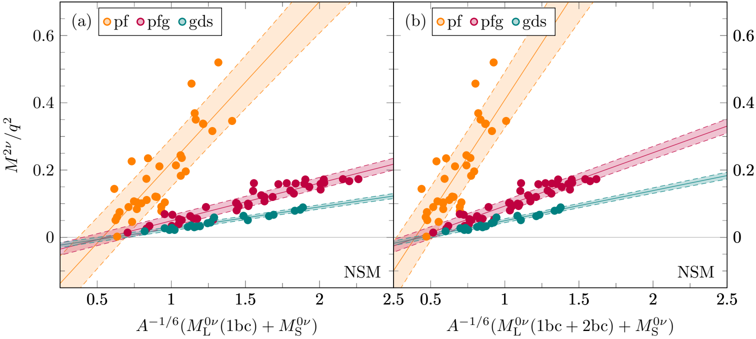
Previous theoretical uncertainty mostly ignored: collection of calculations



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

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

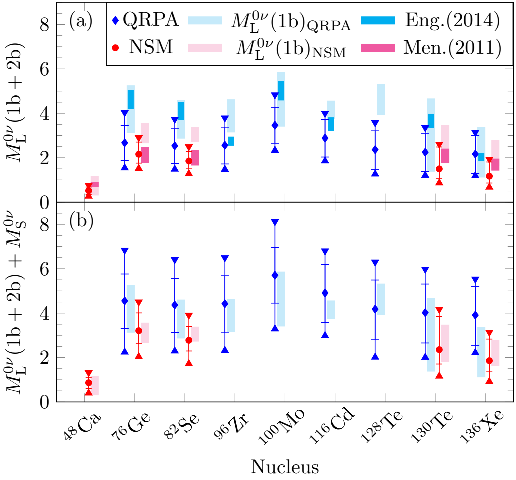
$0\nu\beta\beta$ NMEs from correlation: 2bc, short-range

$0\nu\beta\beta$ 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)



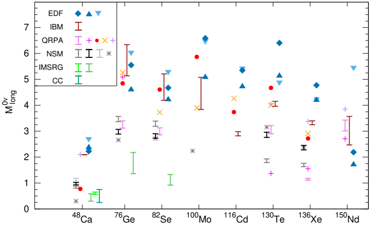
Summary

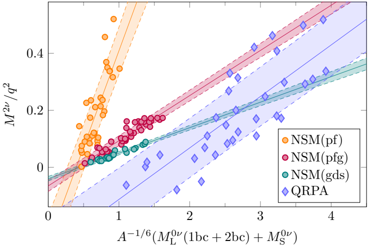
Calculations of $0\nu\beta\beta$ NMEs
challenge nuclear many-body methods,
searches demand reliable NMEs

Ab initio results suggest reduced NMEs
due to nuclear correlations (eg via GCF)
and two-body currents

Likely enhancement by short-range NME
partially compensates reduction
due to correlations and currents

Good $0\nu\beta\beta - 2\nu\beta\beta$ correlation
in nuclear shell model, QRPA
exploit $2\nu\beta\beta$ data to obtain $0\nu\beta\beta$ NMEs
with theoretical uncertainties





Collaborators

Universitat de Barcelona	J. P. Linares, **P. Soriano**
TRIUMF	**L. Jokiniemi**
LSC Laboratorio Subterráneo Canfranc	C. Peña-Garay, **B. Romeo**
	N. Shimizu
Los Alamos National Laboratory EST. 1943	**R. Weiss**
Argonne National Laboratory	A. Lovato, B. Wiringa
Technische Universität Darmstadt	**C. Brase**, A. Schwenk