Search for neutrinoless $\beta\beta$ decays

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Outline

Neutrinoless $\beta\beta$ decay

Nuclear matrix elements

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

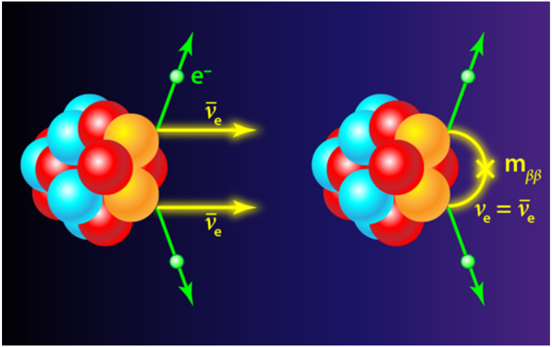
Lepton number conserved in all processes observed:

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)



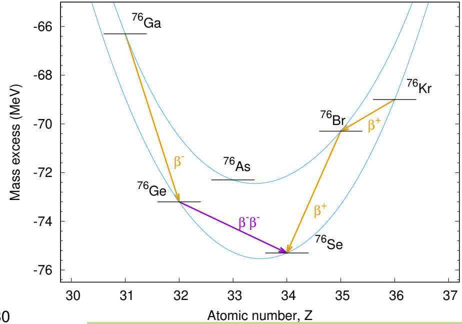
$\beta\beta$ decay

Second order process in the weak interaction

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

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

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



$^{48}Ca \rightarrow {}^{48}Ti$
$^{76}Ge \rightarrow {}^{76}Se$
$^{82}Se \rightarrow {}^{82}Kr$
$^{96}Zr \rightarrow {}^{96}Mo$
$^{100}Mo \rightarrow {}^{100}Ru$
$^{110}Pd \rightarrow {}^{110}Cd$
$^{116}Cd \rightarrow {}^{116}Sn$
$^{124}Sn \rightarrow {}^{124}Te$
$^{130}Te \rightarrow {}^{130}Xe$
$^{136}Xe \rightarrow {}^{136}Ba$
$^{150}Nd \rightarrow {}^{150}Sm$

Scales in new-physics searches using nuclei

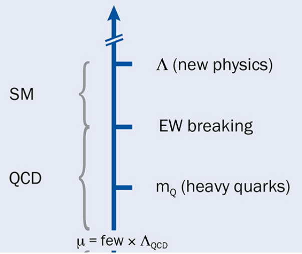
New physics scale: $\Lambda \gg 250$ GeV

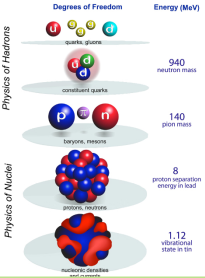
Electroweak scale:

$$v = \left(\sqrt{2}G_F\right)^{-1/2} \sim 250 \text{ GeV}$$

QCD (hadron) scale: $m_N \sim$ GeV

Nuclear scale: $k_F \sim m_\pi \sim 200$ MeV





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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

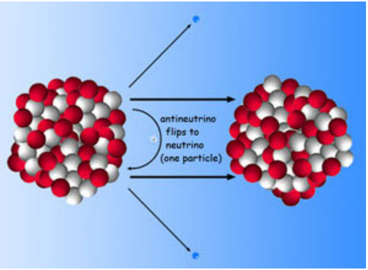
$$0\nu\beta\beta: \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

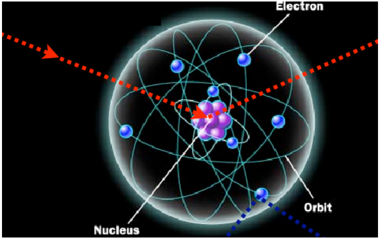
$$\text{Dark matter: } \frac{d\sigma_{\chi\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$$

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

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

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

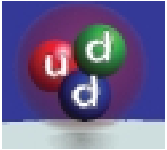


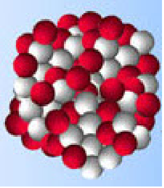


Particle, hadron and nuclear physics

χ scattering off nuclei (direct dark matter detection)
interplay of particle, hadron and nuclear physics:

χ's: interaction with quarks and gluons
Quarks and gluons: embedded in the nucleon
Nucleons: form complex, many-nucleon nuclei





General χ-nucleus scattering cross-section:

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

ζ: kinematics $(q^2, \cdots)$

c coefficients:
χ couplings to quark, gluons (Wilson coefficients), particle physics
convoluted with hadron matrix elements, hadron physics

$\mathcal{F}$ functions: $\mathcal{F}^2 \sim$ structure factor, nuclear structure physics

$0\nu\beta\beta$ decay half-life

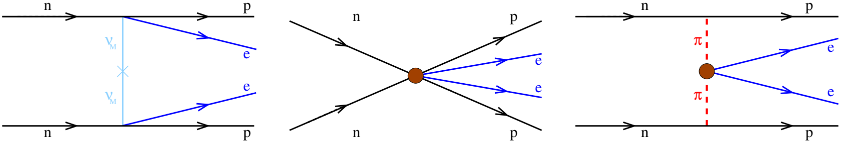
Half-life of $0\nu\beta\beta$ decay sensitive to
$m_{\beta\beta} \sim 1/\Lambda$ (dim-5 operator), new-physics scales $\widetilde{\Lambda}$ (dim-7) or $\widetilde{\Lambda}'$ (dim-9)

$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M^{0\nu}_{\rm light}\right)^2 m_{\beta\beta}^2 + m_N^2\, \tilde{G}\, \tilde{g}^4\, \tilde{M}^2 \left(\frac{v}{\widetilde{\Lambda}}\right)^6 + \frac{m_N^4}{v^2}\, \widetilde{G}'\, \widetilde{g}'^4\, \widetilde{M}'^2 \left(\frac{v}{\widetilde{\Lambda}'}\right)^{10}$$

G_{01}, $\widetilde{G}$, $\widetilde{G}'$: phase-space factors (electrons), very well known

g_A, $g_\nu^{\rm NN}$, $\widetilde{g}$, $\widetilde{g}'$: coupling to hadron(s), experiment or calculate with QCD

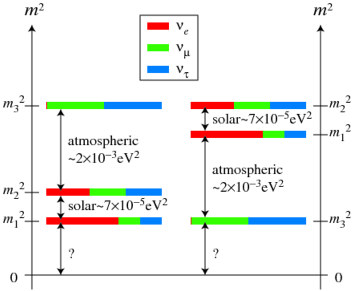
$M^{0\nu}_{\rm long}$, $M^{0\nu}_{\rm short}$, $\widetilde{M}$, $\widetilde{M}'$: nuclear matrix elements, many-body challenge

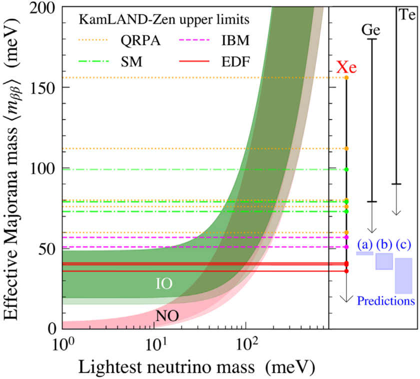


Next generation experiments: inverted hierarchy

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

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





KamLAND-Zen, PRL130 051801(2023)

Matrix elements assess
if next-generation experiments
fully cover "inverted hierarchy"

$0\nu\beta\beta$ decay mediated by sterile neutrinos

- Dependence of the NME on m_ν:

$$H^X(r) = \frac{2}{\pi}\frac{R}{g_A^2}\int_0^\infty f^X(pr)\frac{h^X(p^2)}{\left(\sqrt{p^2+m_\nu^2}\right)\left(\sqrt{p^2+m_\nu^2}+\langle E^m\rangle-\frac{1}{2}(E_i-E_f)\right)}p^2\,dp$$

- Dependence of two-body coupling $g_\nu^{\rm NN}$ on m_ν
- $m_\nu \gtrsim 1$ GeV, integrate ν's out at the quark level, match to lepton-number-violating operator

Cancellation: $\sum_{i=1}^{n+3} U_{ei}^2 m_i = (M_\nu)^*_{ee} = 0$

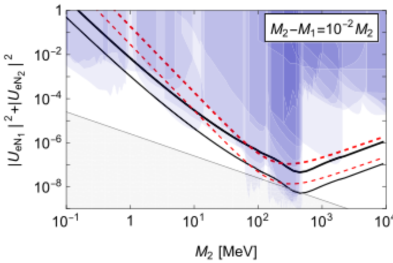
Blennow et al. JHEP 07 096 (2010)

Drives subleading (N^{2}LO) NME

ultrasoft ν's: low-momentum $p \ll m_\pi$ dominant because of milder scaling

Dekens et al. PRC 108 045501 (2023)

Dekens et al. JHEP 09 201 (2024)



$0\nu\beta\beta$ mediated by new-physics heavy particles

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

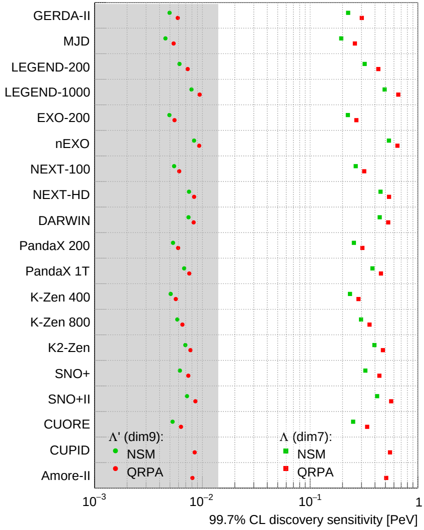
Phase-space,
hadronic/nuclear matrix elements,
known or calculated

Effective field theory

Cirigliano et al JHEP 12 097 (2018)

dimension-7 ($\sim 1/\Lambda^3$),
dimension-9 ($\sim 1/\Lambda^5$) operators

constrained by current searches
$\Lambda \gtrsim 250$ TeV (dim-7)
$\Lambda \gtrsim 5$ TeV (dim-9)



Outline

Neutrinoless $\beta\beta$ decay

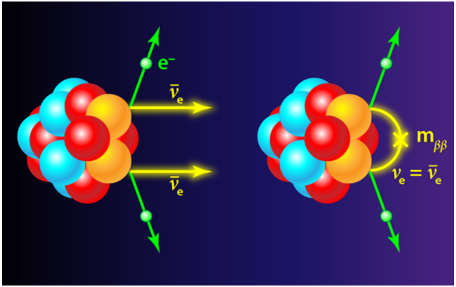
Nuclear matrix elements

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:
  Hadron current in nucleus:
  phenomenological,
  effective theory of QCD



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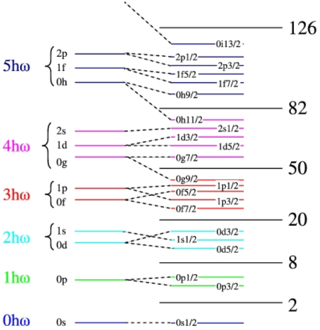
Nuclear shell model



Only keep essential degrees of freedom

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

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

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

Shell model diagonalization:

$\sim 10^{12}$ Slater dets. Caurier et al. RMP77 (2005)

$\gtrsim 10^{30}$ Slater dets. variational

Otsuka, Shimizu, Tsunoda: PScr. 92 063001 (2017)
Dao, Nowacki: PRC 105, 054314 (2022)
Bally, Rodríguez: EPJA 60 62 (2024)

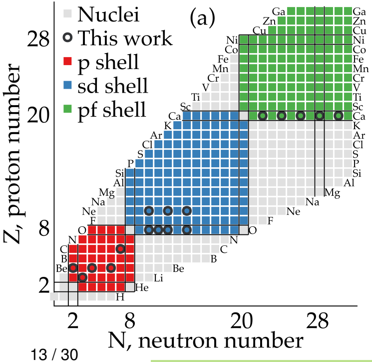
H_{eff} includes effects of

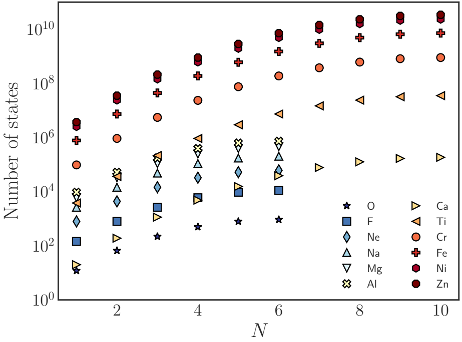
- inert core
- high-energy orbitals

Shell-model scaling

Even for medium-mass nuclei
shell-model calculations become demanding toward the mid-shell

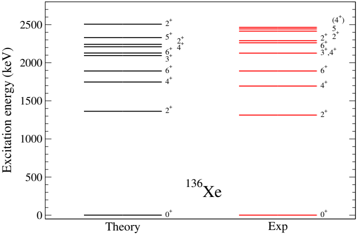
with number of Slater determinants (many-body basis states)
reaching $\sim 10^{10}$ for relatively simple nuclei

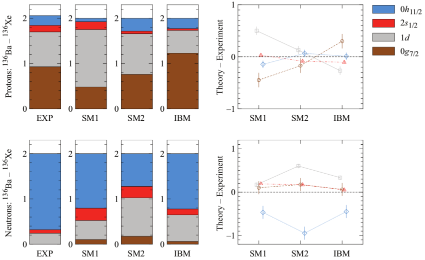


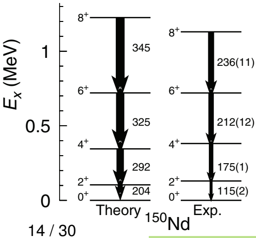


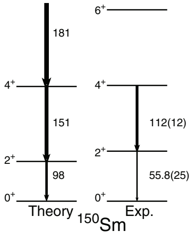
Tests of nuclear structure

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)

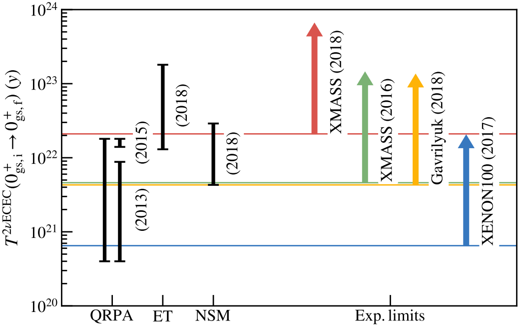
Rodríguez et al. PRL105 252503 (2010)

...

Vietze et al. PRD91 043520 (2015)

$2\nu\beta\beta$ decay, 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

$2\nu\beta\beta$ decay, 2νECEC of ^{124}Xe

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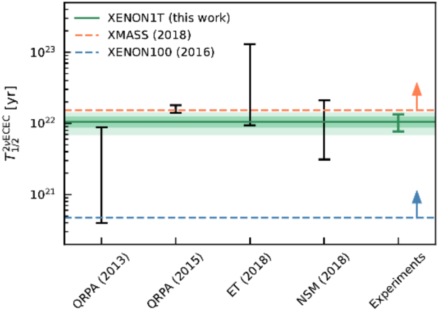

Suhonen
JPG 40 075102 (2013)

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Coello Pérez, JM, Schwenk

PLB 797 134885 (2019)

XENON1T
Nature 568 532 (2019)

PRC106, 024328 (2022)

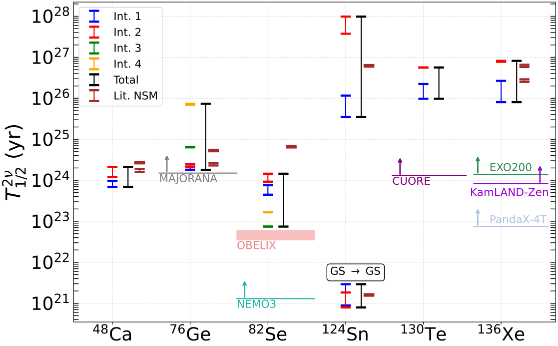
Shell model, QRPA, Effective theory (ET)
good agreement with XENON1T measurement!

$2\nu\beta\beta$ 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

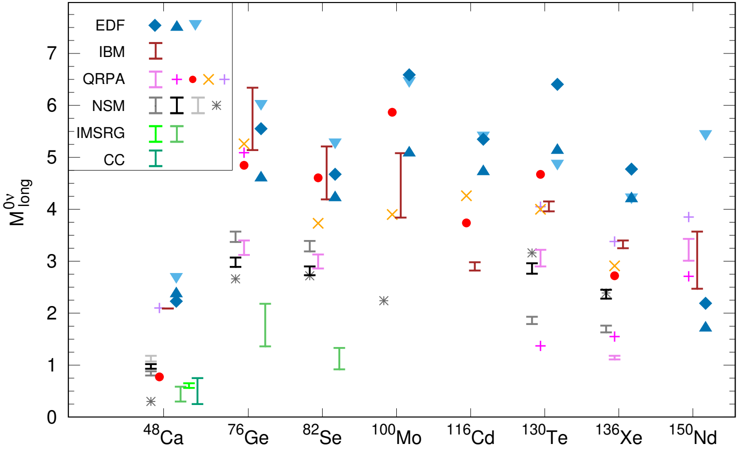
el Morabit et al. JHEP 06 082 (2025)



Large theoretical uncertainty due to nuclear Hamiltonian

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

Large difference in nuclear matrix element calculations



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

Light-neutrino exchange: contact operator

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

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

Cirigliano et al. PRL120 202001(2018)

Unknown value (and sign) of the hadronic coupling $g_\nu^{\rm NN}$!

Lattice QCD calculations could obtain value of $g_\nu^{\rm NN}$

Davoudi, Kadam, Phys. Rev. Lett. 126, 152003 (2021), PRD105 094502('22)

match $nn \to pp + ee$ amplitude calculated with dispersion QCD methods

Cirigliano et al. PRL126 172002 (2021), JHEP 05 289 (2021)

relativistic χEFT $nn \to pp + ee$ amplitude calculation

Yang et al. PRL134, 242502 (2025)

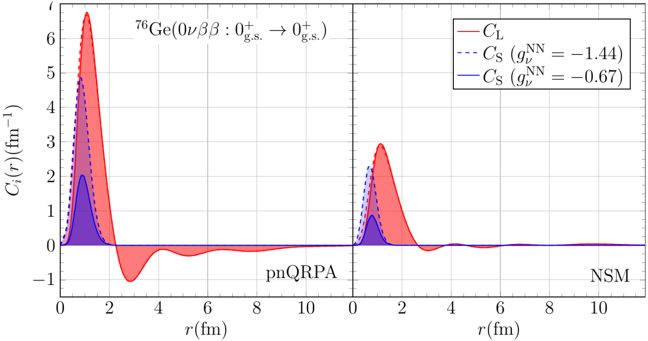
charge-independence breaking of nuclear Hamiltonians

Cirigliano et al. PRC100, 055504 (2019)

Long and short-range NME in heavy nuclei

Relatively stable contribution of new term M_S/M_L
among different nuclei used in $0\nu\beta\beta$ experiments:

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



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

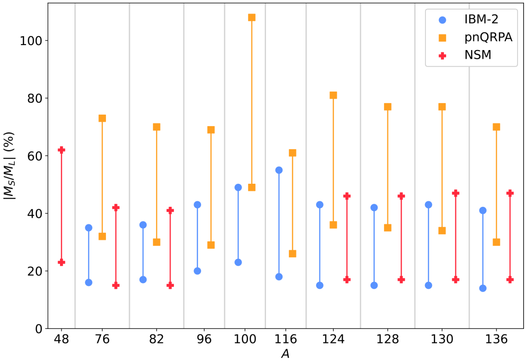
Short-range NME: method comparison

Relatively consistent contribution of M_S/M_L among many-body methods:

20% – 50% in shell model
30% – 70% in QRPA
Jokiniemi, Soriano, JM
Phys. Lett. B 823 136720 (2021)

20% – 50% in IBM
Kauppinen and Kotila
PRC 112, 034329 (2025) (2025)

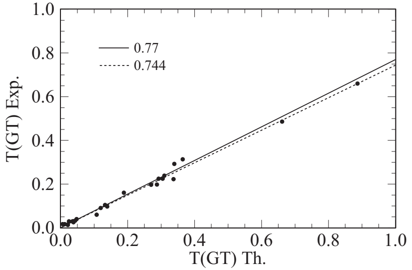
43% in IM-GCM for ^{48}Ca
Wirth et al.
PRL127 242502 (2021)



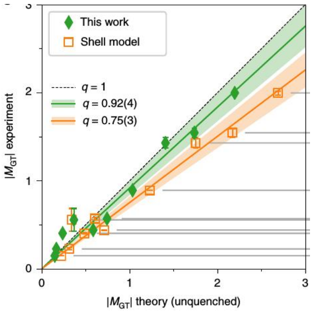
Uncertainty dominated by coupling g_ν^{NN}

β–decay Gamow-Teller transitions: "quenching"

β decays (e^- capture): nuclear shell model vs ab initio



Martinez-Pinedo et al. PRC53 2602(1996)



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

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

Shell model: $\boldsymbol{\sigma}_i\tau$ "quenching"

quenching: effects not in model

Ab initio calculations including meson-exchange currents and additional nuclear correlations

do not need "quenching"

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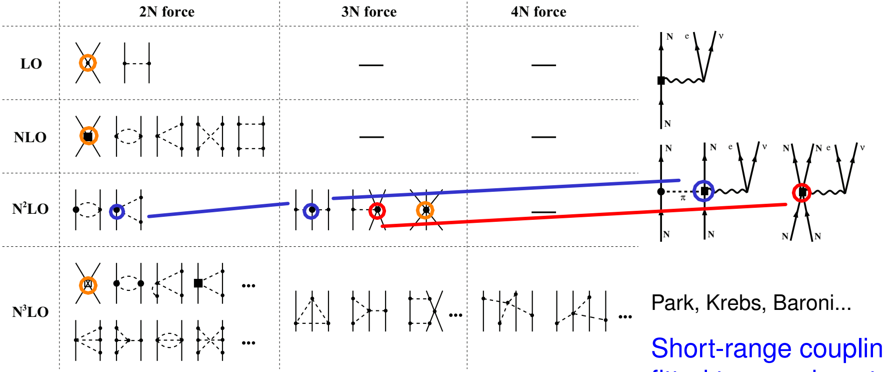
Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



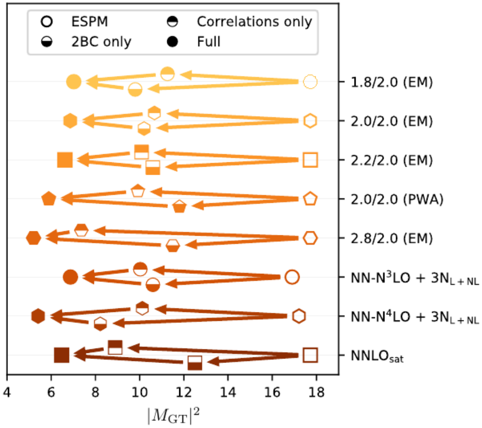
Park, Krebs, Baroni...

Short-range couplings fitted to experiment once

Weinberg, van Kolck, Kaplan, Savage, Wise, Meißner, Epelbaum...

Origin of β decay "quenching"

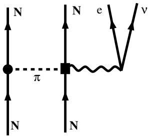
Which are main effects missing in conventional β-decay calculations?
Test case: GT decay of ^{100}Sn



Relatively similar and complementary impact of

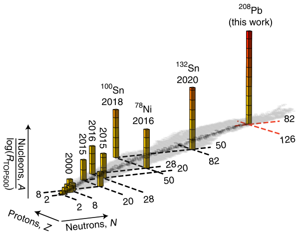
- nuclear correlations
- meson-exchange currents

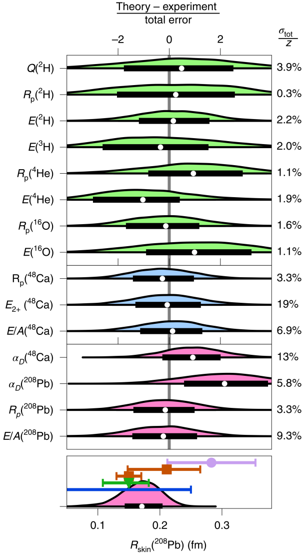
Gysbers et al.
Nature Phys. 15 428 (2019)



Ab initio predictions for nuclear neutron radius

Remarkable progress ab initio calculations of (relatively uncorrelated) heavy nuclei, ^{208}Pb





Determine ^{208}Pb neutron skin using Bayesian approach sampling of 10^9 (parameters of) nuclear Hamiltonians

Hu, Jiang, Miyagi et al.

Nature Phys. 18 1196 (2022)

Correlation analysis: NMEs vs nuclear properties

Use correlation of $0\nu\beta\beta$ with observables to calibrate NME predictions:

Two-neutrino $\beta\beta$ decay

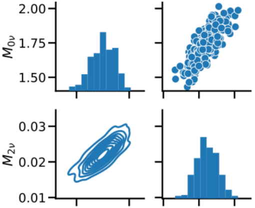
Horoi et al. PRC106 054302(2022), 107 045501(2023)
Jokiniemi et al. PRC107 044305 (2023)

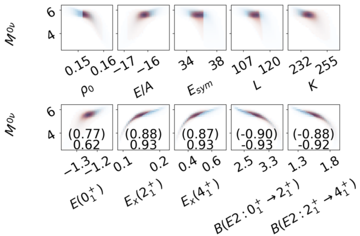
Observables related to nuclear deformation

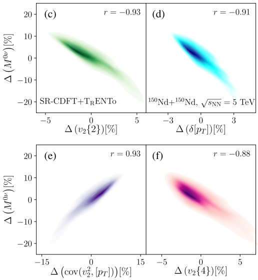
Zhang et al. PRC112 L021302 (2025), Li et al. PRL135 022301 (2025)

Pairing-channel phase-shift at rel. high energy:

Belley et al. arXiv:2408.02169

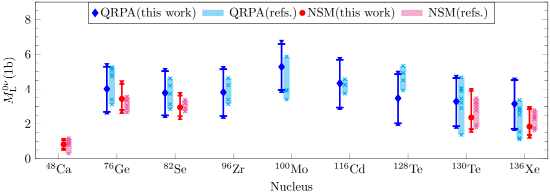


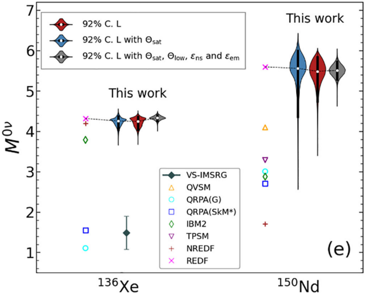




$0\nu\beta\beta$ NMEs with theoretical uncertainties

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





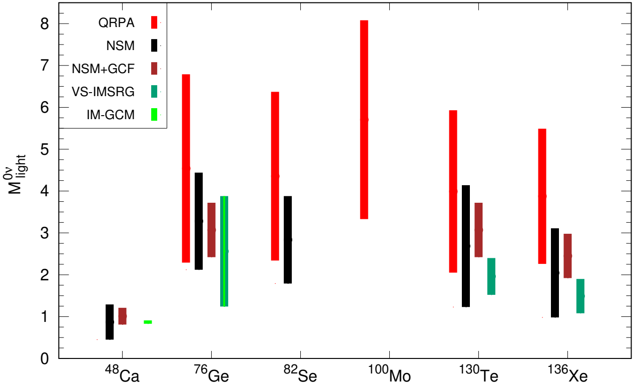
NMEs consistent with previous results,
but also take into account model uncertainties

Jokiniemi et al. PRC107 044305 (2023)

Zhang et al. PRC112 L021302 (2025)

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

Not-so-large difference in nuclear matrix element calculations!



Wirth et al.
PRL127 242502 (2021)

Belley et al.
arXiv:2307:15156

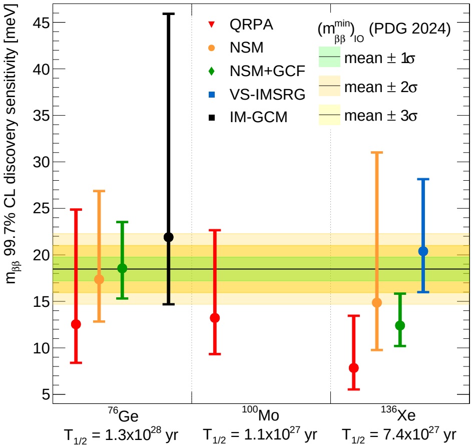
Belley et al.
PRL132 182502 (2024)

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)

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



Agostini, Benato, Detwiler, JM, Vissani

Phys. Rev. C 104 L042501 (2021), updated

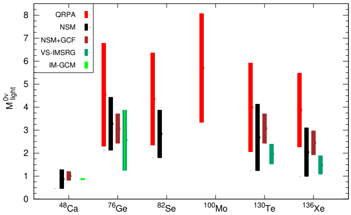
Nuclear matrix element theoretical uncertainty critical to anticipate $m_{\beta\beta}$ sensitivity of future experiments

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

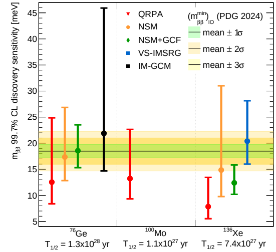
Uncertainty needs to be reduced!

Summary

Calculations of $0\nu\beta\beta$ NMEs
challenge nuclear many-body methods,
reach and exploitation of $0\nu\beta\beta$ searches
demand reliable NMEs
reduce present theoretical uncertainties



Nuclear calculations must describe well
known nuclear spectroscopy
and include physics of "quenching"
and new short-range NME
Calibration with data ($2\nu\beta\beta$, deformation...)
inform theoretical uncertainty of NMEs



Current $0\nu\beta\beta$ NMEs sizeable errorbars
and reasonable overlap of predictions
from different many-body methods

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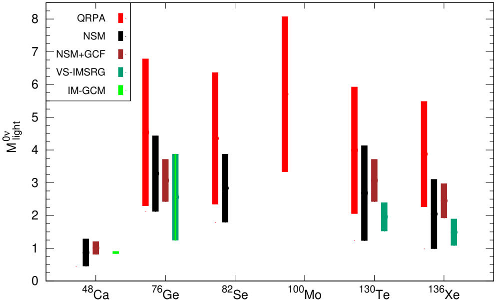
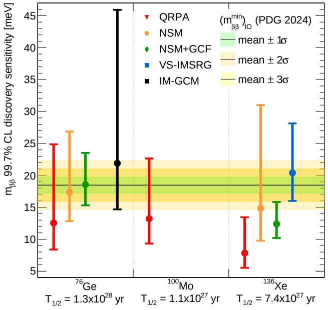
Thank you very much for your attention!

Feel free to ask any questions!



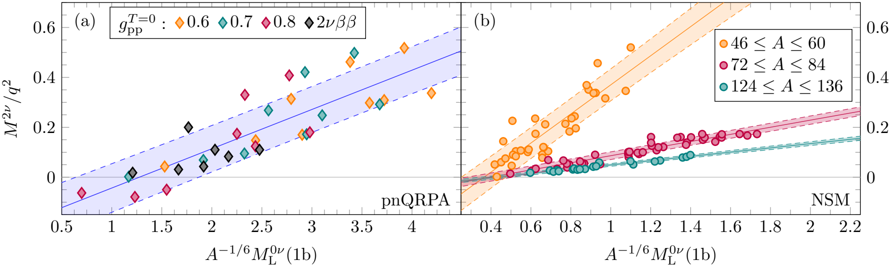


Correlation of $0\nu\beta\beta$ decay and $2\nu\beta\beta$ decay

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. PRC106 054302 (2022), PRC107 045501 (2023)



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