$\gamma\gamma$ decay as a probe of neutrinoless $\beta\beta$ decay nuclear matrix elements

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

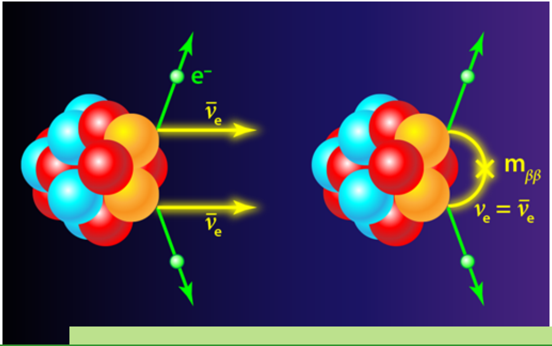
Lepton number is conserved
in all processes observed:

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



Outline

Neutrinoless $\beta\beta$ decay

Nuclear structure experiments for neutrinoless $\beta\beta$ decay

$\gamma\gamma$ decay and $\beta\beta$ decay

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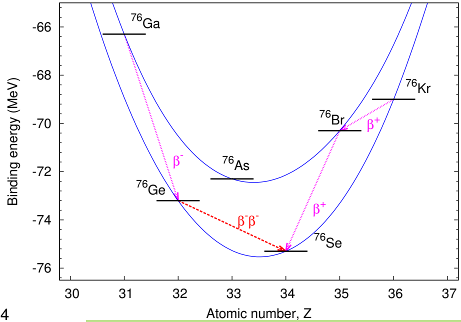
$\beta\beta$ decay

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



^{48}Ca → ^{48}Ti

^{76}Ge → ^{76}Se

^{82}Se → ^{82}Kr

^{96}Zr → ^{96}Mo

^{100}Mo → ^{100}Ru

^{110}Pd → ^{110}Cd

^{116}Cd → ^{116}Sn

^{124}Sn → ^{124}Te

^{130}Te → ^{130}Xe

^{136}Xe → ^{136}Ba

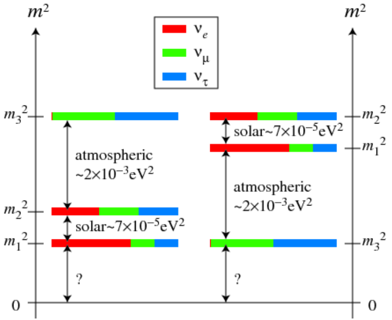
^{150}Nd → ^{150}Sm

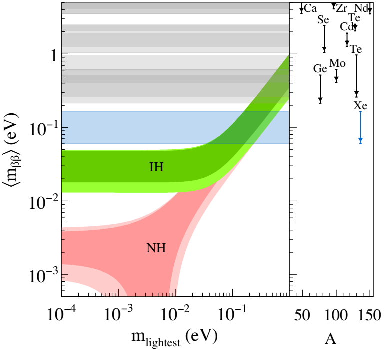
Next generation experiments: inverted hierarchy

Decay rate sensitive to neutrino masses, hierarchy

$m_{\beta\beta} = |\sum U_{ek}^2 m_k|$

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

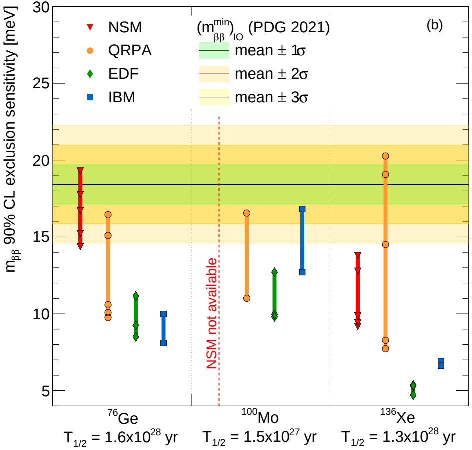




KamLAND-Zen, PRL117 082503(2016)

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!

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Neutrinoless $\beta\beta$ decay

Nuclear structure experiments for neutrinoless $\beta\beta$ decay

$\gamma\gamma$ decay and $\beta\beta$ decay

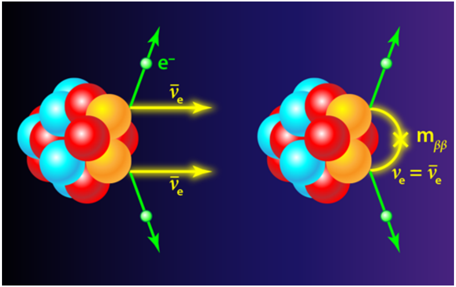
Nuclear matrix elements

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

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

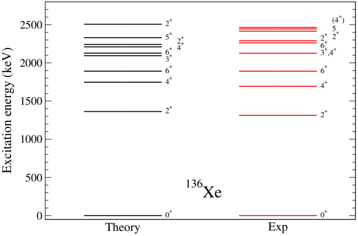
- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  QMC, Coupled-cluster, IMSRG...

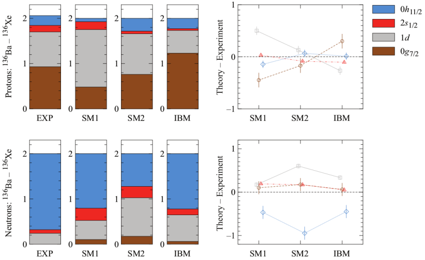
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD

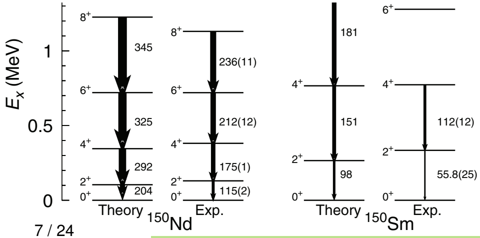


Tests of nuclear structure

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)

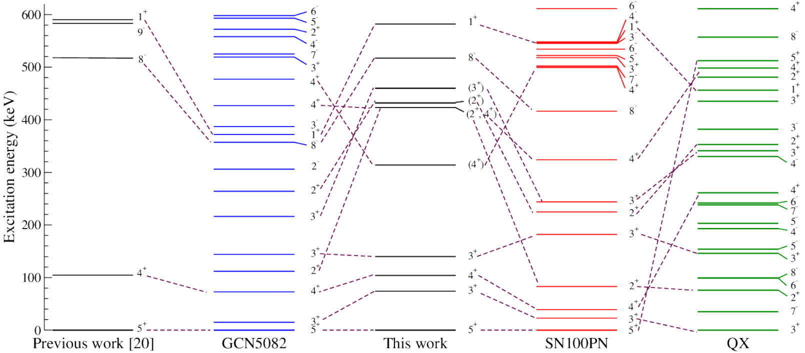
...

Vietze et al. PRD91 043520 (2015)

Nuclear structure of ^{136}Cs

Recent measurement of low-lying states of intermediate nucleus ^{136}Cs sensitive to nuclear shell-model interactions used for $0\nu\beta\beta$ decay

Rebeiro et al. arXiv:2301.11372

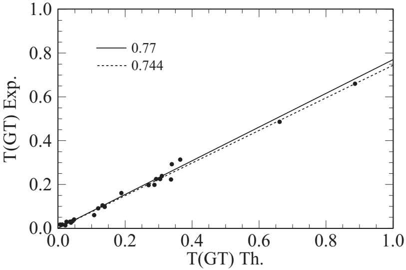


QX interaction does not reproduce ground state

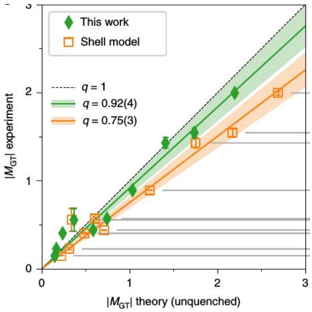
many negative parity states not observed experimentally.

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”

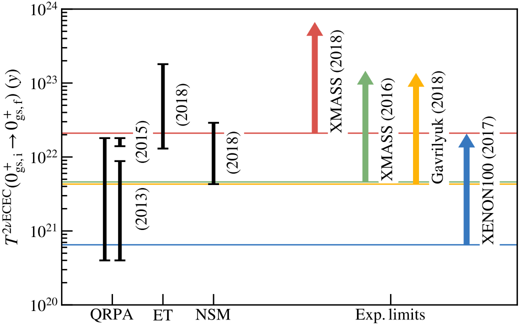
$2\nu\beta\beta$ decay, 2νECEC of ^{124}Xe

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 field theory (ET) predictions suggest experimental detection close to XMASS 2018 limit

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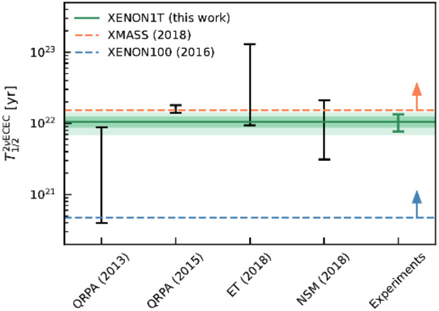


Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

Coello Pérez, JM, Schwenk

PLB 797 134885 (2019)

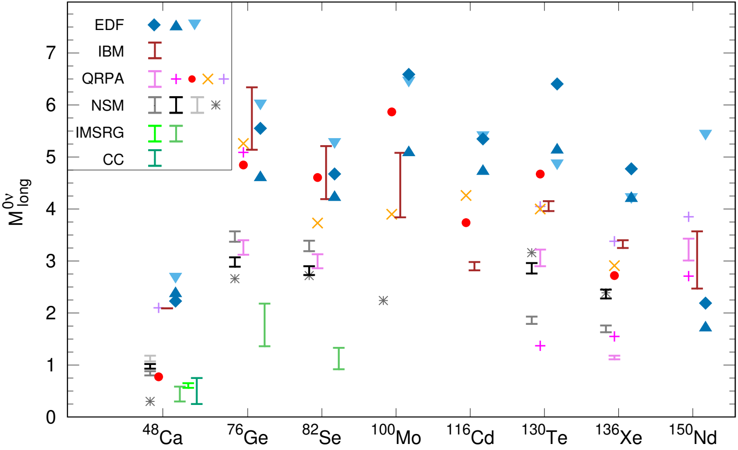
XENON1T
Nature 568 532 (2019)

PRC106, 024328 (2022)

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

$0\nu\beta\beta$ 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

Light-neutrino exchange: contact operator

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

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

Cirigliano et al. PRL120 202001(2018)

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

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

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

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

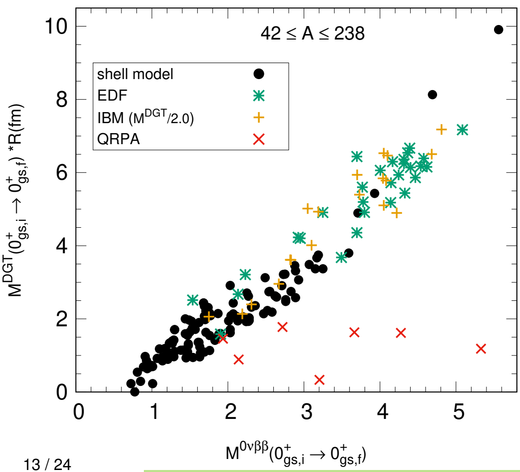
Davoudi, Kadam, Phys. Rev. Lett. 126, 152003 (2021), arXiv:2111.11599

or match $nn \to pp + ee$ amplitude calculated with approximate QCD

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

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

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



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

Shimizu, JM, Yako
PRL120 142502 (2018)

Common to shell model energy-density functionals interacting boson model, ab initio methods (weaker)

Yao et al. PRC106 014315(2022)

Experiments at RIKEN, INFN, RCNP? access DGT transitions

Outline

Neutrinoless $\beta\beta$ decay

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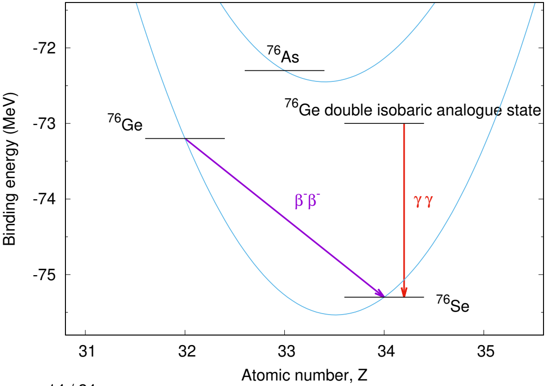
$\gamma\gamma$ decay and $\beta\beta$ decay

$\gamma\gamma$ 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

$$M^{\gamma\gamma}_{M1\,M1} = \sum_k \frac{\langle 0^+_f | \sum_n (g^l_n \boldsymbol{l}_n + g^s_n \boldsymbol{\sigma}_n)^{IV} | 1^+_k(\mathrm{IAS})\rangle \langle 1^+_k(\mathrm{IAS}) | \sum_m (g^l_m \boldsymbol{l}_m + g^s_m \boldsymbol{\sigma}_m)^{IV} | 0^+_i(\mathrm{DIAS})\rangle}{E_k - (E_i + E_f)/2}$$



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)

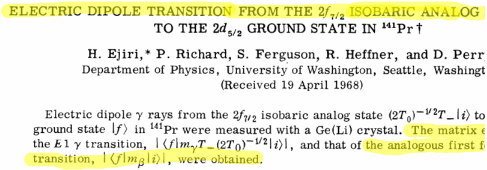
β decays and γ transitions from IAS

The relation between electromagnetic decays from IAS and weak ones has been used and tested many times

Ejiri, Suhonen, Zuber, Phys. Rept. 797 1 (2019)

Fujita, Rubio, Gelletly, Prog. Part. Nucl. Phys.66, 549 (2011)

And it is certainly not a novel idea...

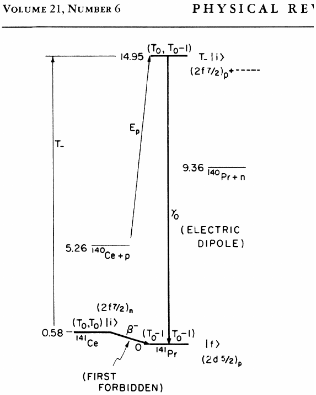


ELECTRIC DIPOLE TRANSITION FROM THE $2f_{7/2}$ ISOBARIC ANALOG
TO THE $2d_{5/2}$ GROUND STATE IN ^{141}Pr †

H. Ejiri,* P. Richard, S. Ferguson, R. Heffner, and D. Perr
Department of Physics, University of Washington, Seattle, Washingt
(Received 19 April 1968)

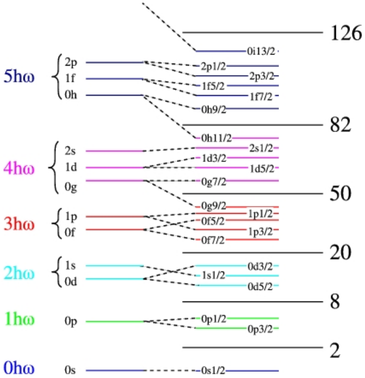
Electric dipole γ rays from the $2f_{7/2}$ isobaric analog state $(2T_0)^{-1/2}T_-|i\rangle$ to ground state $|f\rangle$ in ^{141}Pr were measured with a Ge(Li) crystal. The matrix e the $E1$ γ transition, $|\langle f|m_\gamma T_-(2T_0)^{-1/2}|i\rangle|$, and that of the analogous first f transition, $|\langle f|m_\beta|i\rangle|$, were obtained.

PRL 21 373 (1968)



VOLUME 21, NUMBER 6 PHYSICAL RE

Nuclear shell model



Nuclear shell model configuration space 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:

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

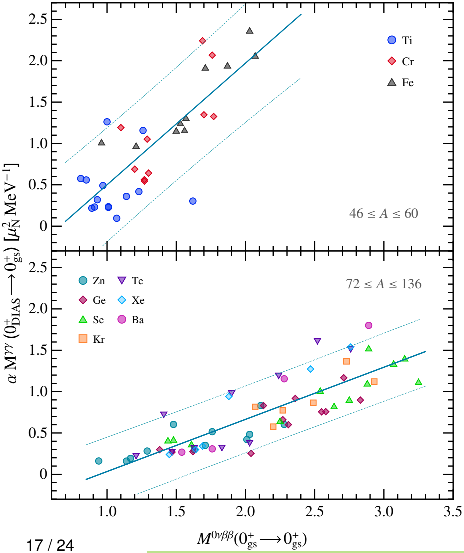
$\gtrsim 10^{24}$ Slater dets. with Monte Carlo SM

Otsuka, Shimizu, Y.Tsunoda

H_{eff} includes effects of

- inert core
- high-energy orbitals

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



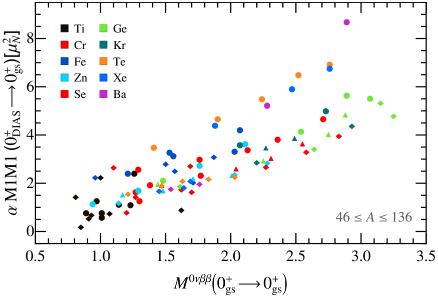
Good correlation between $M1M1$ same-energy photons and shell-model $0\nu\beta\beta$ NMEs

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

Overall, study $\sim$ 50 transitions several nuclear interactions for each of them

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

Intermediate states of the $M1M1$ transition



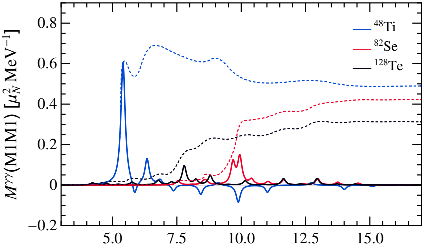
When energy denominators are (artificially) removed, same correlation across the nuclear chart

Romeo, JM, Peña-Garay

PLB 827 136965 (2022)

Dominant intermediate states lower energies for lighter nuclei, otherwise similar energies

One or few intermediate states typically dominate the transition

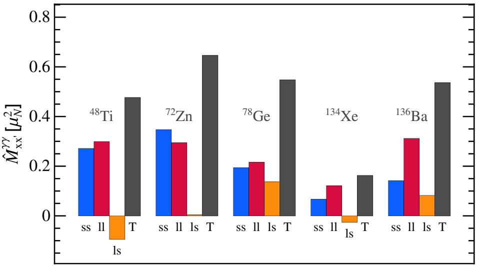


Spin, angular momentum decomposition

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

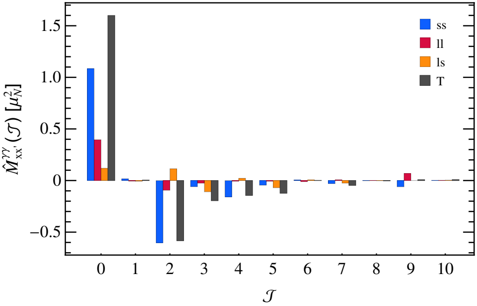
Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Total angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{\gamma\gamma}(\mathcal{J}) = \hat{M}_{ss}(\mathcal{J}) + \hat{M}_{ll}(\mathcal{J}) + \hat{M}_{ls}(\mathcal{J})$$

spin, angular momentum and interference components
and total angular momentum of the nucleons involved in the transition



Dominance of $\mathcal{J} = 0$ terms
for spin and orbital contributions
just like in $0\nu\beta\beta$ decay

Cancellation from $\mathcal{J} > 0$ terms
less pronounced in orbital part

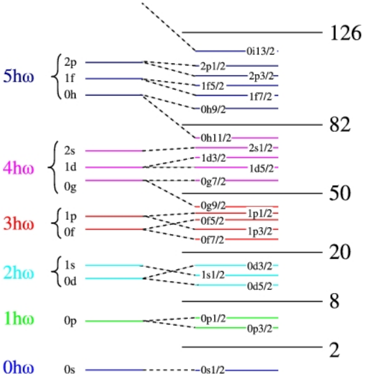
Explains similar behaviour of
spin and orbital components:

$$s_1\, s_2 = \mathcal{S}^2 - 3/2 < 0$$

$$l_1\, l_2 = \mathcal{L}^2 - l_1^2 - l_2^2 < 0$$

Romeo et al. PLB 827 136965 (2022)

QRPA method



QRPA configuration space
comprises 18–25 single-particle orbitals
with no core in the calculation

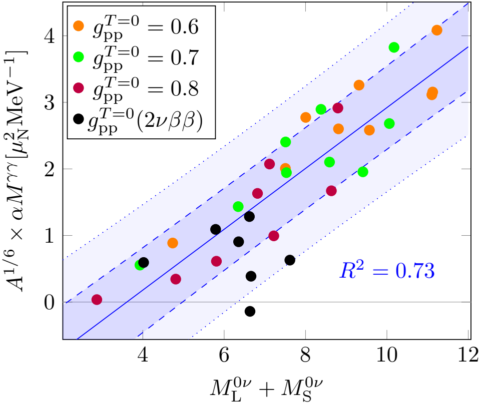
Intermediate states in odd-odd nuclei
described as
proton-neutron quasiparticles
from ground states of initial and final
nuclei

More limited nuclear correlations
than nuclear shell model

Some adjustable parameters:
especially particle-particle channel g_{pp} (isoscalar pairing)
critical for a good description of $\beta\beta$ decays

Vogel, Zirnbauer, PRL 57, 3148 (1986), Engel, Vogel, Zirnbauer, PRC 37 3148 (1988)

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



Jokiniemi, JM, arXiv:2302.05399

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

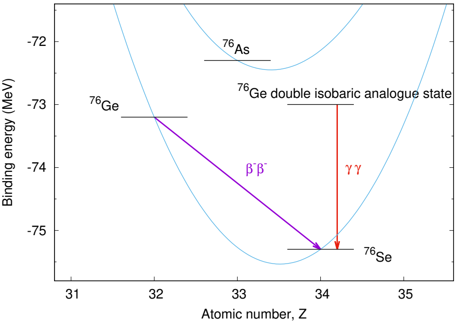
Study of dozen $\beta\beta$ nuclei varying the proton-neutron pairing strength

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 have been observed recently
in competition with γ decays

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



Outlook:

Study in detail leading decay channels for $M1M1$ decay in DIAS of $\beta\beta$ nuclei

Particle emission $M1$, $E1$ decay: BR $\sim 10^{-7} - 10^{-8}$

Experimental proposal for ^{48}Ti by Valiente-Dobón et al.

Valiente-Dobón, Romeo et al., in prep

Summary

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

Nuclear structure measurements:
spectra, β decay, $2\nu\beta\beta$ decay
can inform us on the NME values

Double Gamow-Teller transitions,
electromagnetic *M*1*M*1 decay of DIAS
very good correlation with $0\nu\beta\beta$ NMEs

May be exploited in future experiments
but challenging: BR $\sim 10^{-7} - 10^{-8}$
to gain insight on the NME values