How to measure neutrinoless double-beta decay nuclear matrix elements?

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Neutrinos ElectroWeak interactions and Symmetries
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Universitat de Barcelona

Investigación Programa Ramón y Cajal

ICCUB

Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

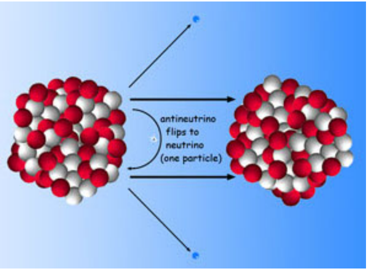
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

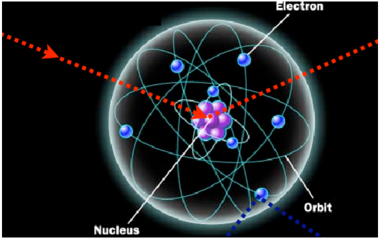
$0\nu\beta\beta$: $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$

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

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

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





Outline

$0\nu\beta\beta$ decay: huge potential, great challenge

Nuclear structure data as test of $0\nu\beta\beta$ calculations

Double Gamow-Teller transitions and $0\nu\beta\beta$ decay

$\gamma\gamma$ transitions and $0\nu\beta\beta$ decay

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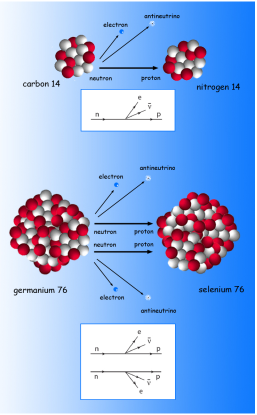
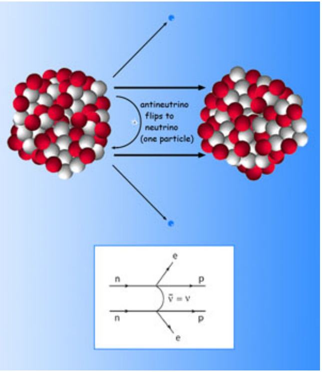
Lepton-number conservation

Lepton number is conserved
in all processes observed

Uncharged massive particles
like Majorana neutrinos (ν)
allow lepton number violation



β decay, $\beta\beta$ decay...



Neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay

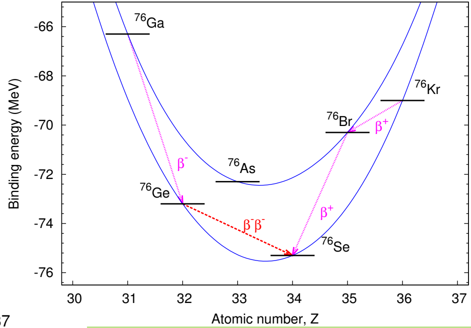
$\beta\beta$ decay

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

$0\nu\beta\beta$ decay rate

$0\nu\beta\beta$ rate depends on kinematics and physics at very different scales:

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}\left(0_i^+ \rightarrow 0_f^+\right)} = G_{01}\, g_A^4 \left|M^{0\nu\beta\beta}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

G_{01} is the phase space factor, kinematics:
accurate calculations; depends on $Q_{\beta\beta}$, charge number Z, electrons...

g_A is the coupling to the nucleon
hard to compute (lattice QCD) but can be measured in other decays

$M^{0\nu\beta\beta}$ is the nuclear matrix element (NME)
nuclear structure of the initial and final nuclei

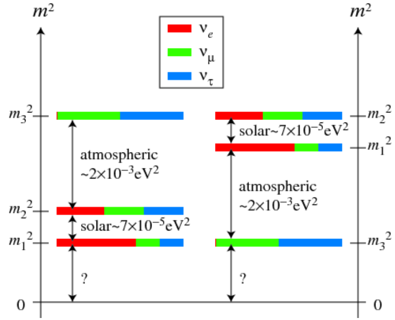
$m_{\beta\beta} = |\sum U_{ek}^2 m_k|$, new physics responsible for lepton-number violation

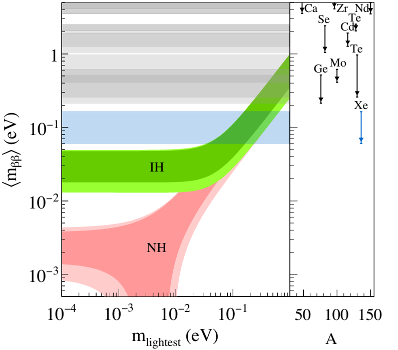
For $0\nu\beta\beta$ rate dominated by different new physics, same structure
different values of G, g, M and $m_{\beta\beta} \sim 1/\Lambda, v^3/\Lambda^3, v^5/\Lambda^5$

Next generation experiments: inverted hierarchy

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

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





Matrix elements assess if
next generation experiments
fully explore "inverted hierarchy"

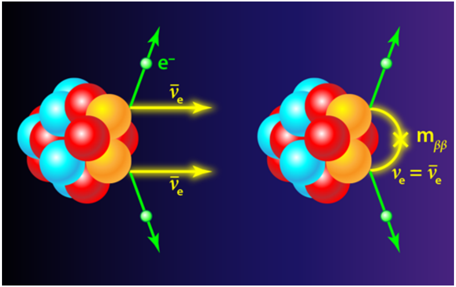
KamLAND-Zen, PRL117 082503(2016)

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
  GFMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD



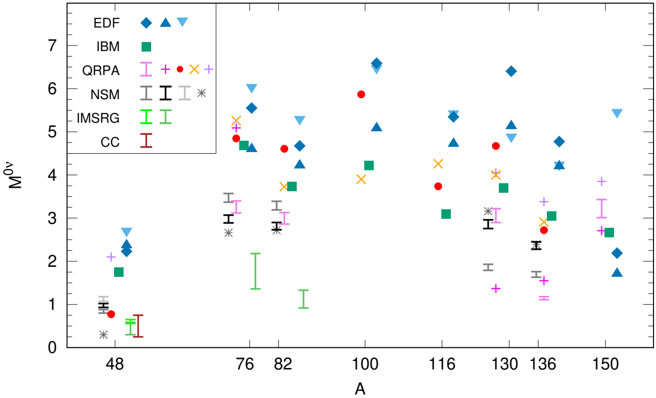
$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations: factor $\sim 2-3$

$$\langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\, \Omega^X \, | 0_i^+ \rangle$$

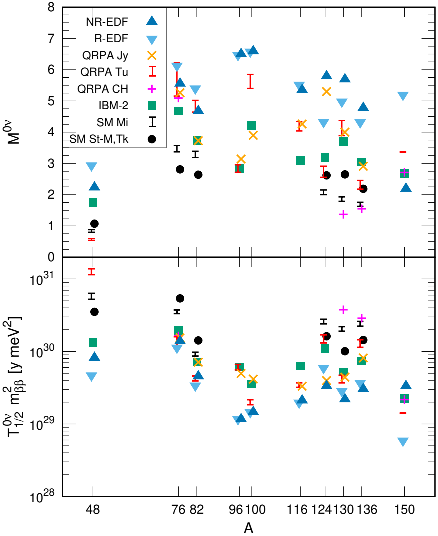
Ω^X = Fermi ($\mathbb{1}$), GT ($\sigma_n \sigma_m$), Tensor

$H(r)$ = neutrino potential



Engel, JM, Rep. Prog. Phys. 80 046301 (2017), updated

Uncertainty in physics reach of $0\nu\beta\beta$ half-lives



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

Order of magnitude uncertainty in $T^{0\nu}_{1/2}$ needs to be reduced!

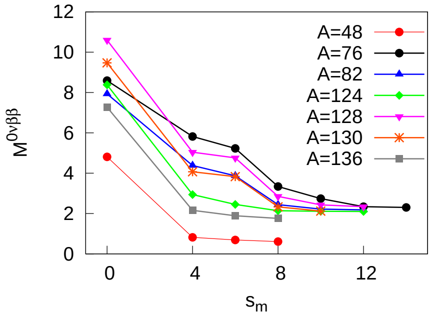
Engel, JM,

Rep. Prog. Phys. 80 046301 (2017)

Pairing correlations and $0\nu\beta\beta$ decay

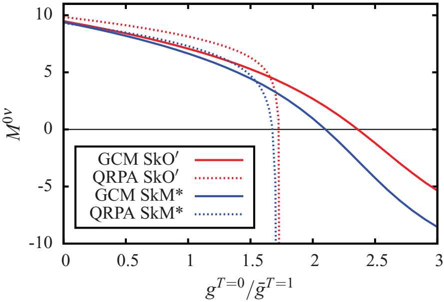
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing, but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix element value



Hinohara, Engel PRC90 031301 (2014)

Related to approximate $SU(4)$ symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator

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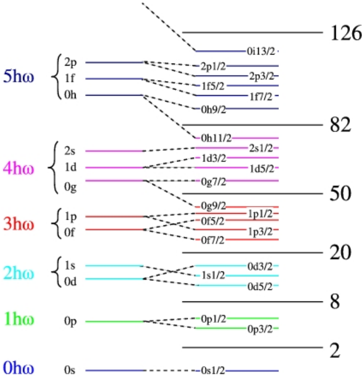
Nuclear shell model



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

$$H\left|\Psi\right\rangle = E\left|\Psi\right\rangle \ \rightarrow H_{eff}\left|\Psi\right\rangle_{eff} = E\left|\Psi\right\rangle_{eff}$$

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

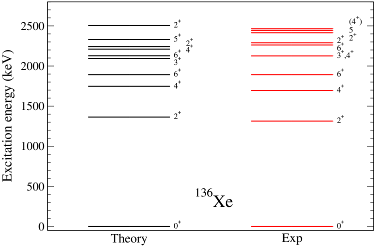
Shell model diagonalization:
$\sim 10^{10}$ Slater dets. Caurier et al. RMP77 (2005)
$\gtrsim 10^{24}$ Slater dets. with Monte Carlo SM Otsuka, Shimizu, Y.Tsunoda

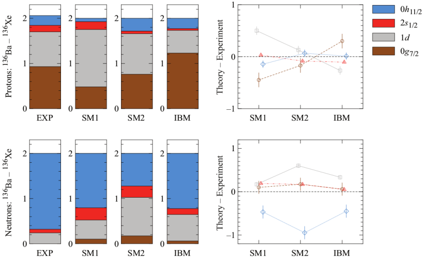
H_{eff} includes effects of

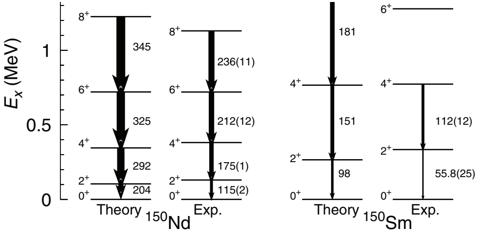
- inert core
- high-energy orbitals

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)

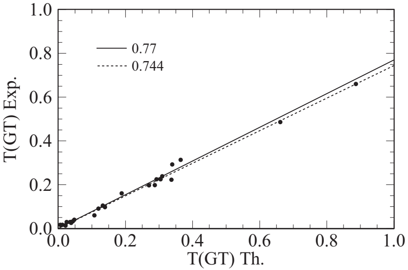
Rodríguez et al. PRL105 252503 (2010)

...

Vietze et al. PRD91 043520 (2015)

β–decay Gamow-Teller transitions: “quenching”

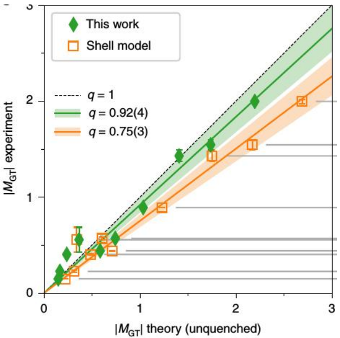
β decays (e^- capture): phenomenology vs ab initio



Martinez-Pinedo et al. PRC53 2602(1996)

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

Standard shell model needs $\boldsymbol{\sigma}_i \tau$ “quenching”

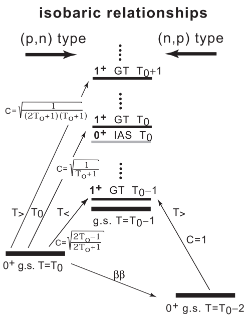


Gysbers et al. Nature Phys. 15 428 (2019)

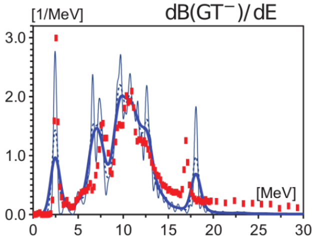
Ab initio calculations including meson-exchange currents do not need any “quenching”

Gamow-Teller strength distributions

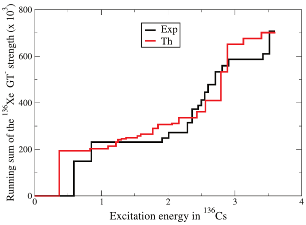
GT strength distribution complements β-decay beyond Q-value region



Frekers et al.
NPA916 219 (2013)



Iwata et al. JPSCP6 3057 (2015)



Caurier et al. PLB711 62 (2012)

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

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

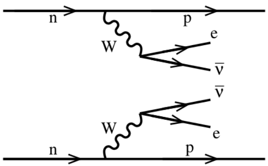
Similar "quenching" q= 0.57 needed in GT decays in xenon mass region
Smaller "quenching" q= 0.42 needed in $2\nu\beta\beta$ of ^{136}Xe

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)



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

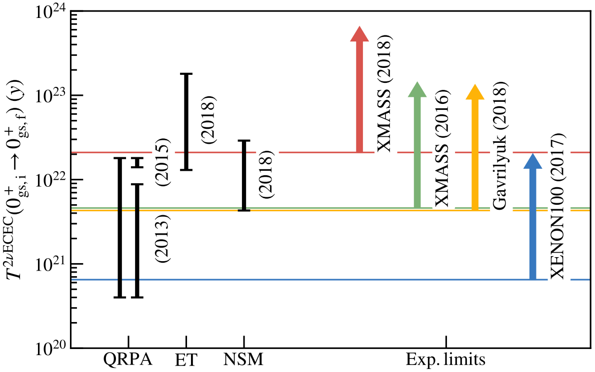
Table 2
The ISM predictions for the matrix element of several 2ν double beta decay (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(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

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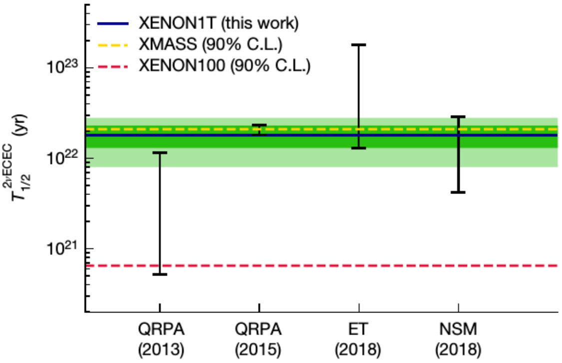


Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

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

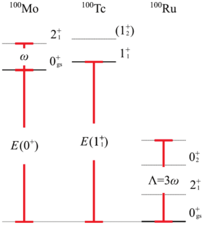
XENON1T
Nature 568 532 (2019)

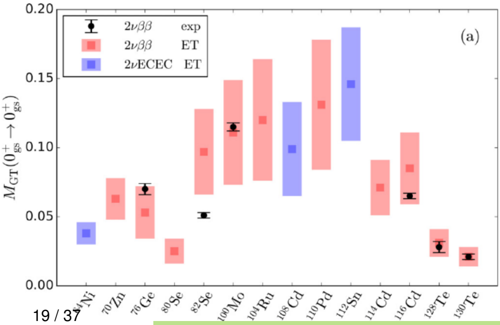
Shell model, QRPA and Effective theory (ET) predictions
good agreement with XENON1T measurement of 2νECEC!

Effective theory of $\beta\beta$ decay

Effective theory (ET) for $\beta\beta$ decay:
spherical core coupled to one nucleon

Couplings adjusted to experimental data,
uncertainty given by effective theory
(breakdown scale, systematic expansion)





Use β-decay data
to predict $2\nu\beta\beta$ decay
Good agreement, large error
(leading-order in ET)

Coello-Pérez, JM, Schwenk
PRC 98, 045501 (2018)

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

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

$$(T^{2\nu}_{1/2})^{-1} \simeq g_A^4 \left|(M^{2\nu}_{GT})^2 G^{2\nu}_0 + M^{2\nu}_{GT} M^{2\nu}_{GT-3} G^{2\nu}_2 + ...\right|$$

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

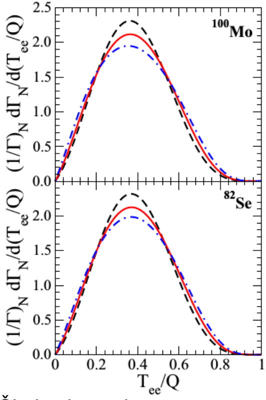
$$M^{2\nu}_{GT3} = \sum_j \frac{4\langle 0^+_f | \sum_l \boldsymbol{\sigma}_l \tau^-_l | 1^+_j \rangle \langle 1^+_j | \sum_l \boldsymbol{\sigma}_l \tau^-_l | 0^+_i \rangle}{\Delta^3},$$

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

Electron differential decay rate:

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

Exp. sensitivity to $\xi^{2\nu}_{31} = M^{2\nu}_{GT-3}/M^{2\nu}_{GT}$

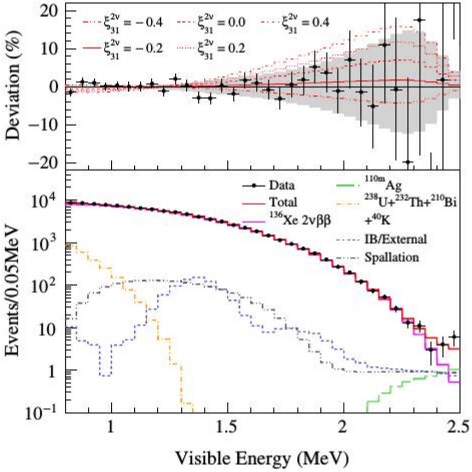


Šimkovic et al.
PRC98 064325 (2018)

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

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

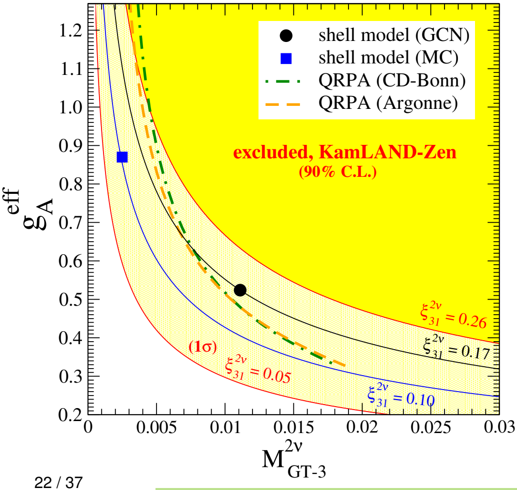
KamLAND-Zen $2\nu\beta\beta$ analysis excludes larger values of $\xi_{31}^{2\nu}$



KamLAND-Zen, PRL122 192501 (2019)

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 (“quenching”)

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

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Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance
in double charge-exchange reactions ^{48}Ca(pp,nn)^{48}Ti proposed in 80's

Auerbach, Muto, Vogel... 1980's, 90's

Recent experimental plans in RCNP, RIKEN (^{48}Ca), INFN Catania

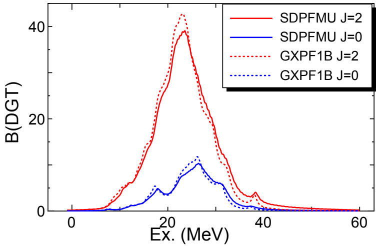
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

Capuzzello et al. EPJA 51 145 (2015), Takahisa, Ejiri et al. arXiv:1703.08264

Promising connection to $\beta\beta$ decay,
two-particle-exchange process,
especially the (tiny) transition
to ground state of final state

Shell model calculation

Shimizu, JM, Yako, PRL120 142502 (2018)



$$B(DGT^-;\lambda;i\to f)=\frac{1}{2J_i+1}\left|\left\langle {}^{48}\mathrm{Ti}\left|\left|\left[\sum_i \boldsymbol{\sigma}_i\tau_i^- \times \sum_j \boldsymbol{\sigma}_j\tau_j^-\right]^{(\lambda)}\right|\right| {}^{48}\mathrm{Ca}_{gs}\right\rangle\right|^2$$

Double Gamow-Teller distribution and pairing

Study the sensitivity of Double GT distribution to pairing correlations

Add/remove pairing

$$H' = H + G^{JT} P^{JT}$$

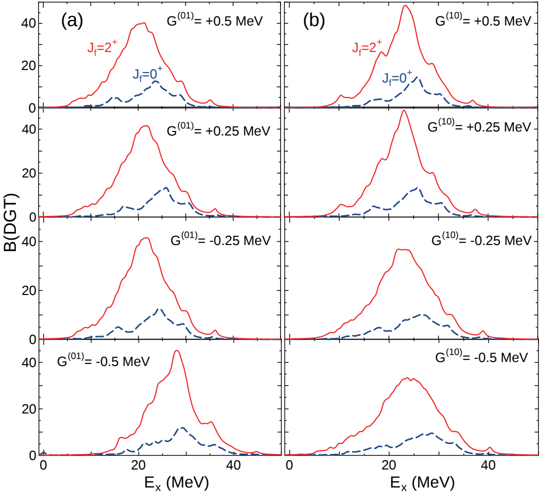
like-particle (T=1) or proton-neutron (T=0)

Position of the DGT giant resonance very sensitive to like-particle pairing

DGT resonance width probes isoscalar pairing

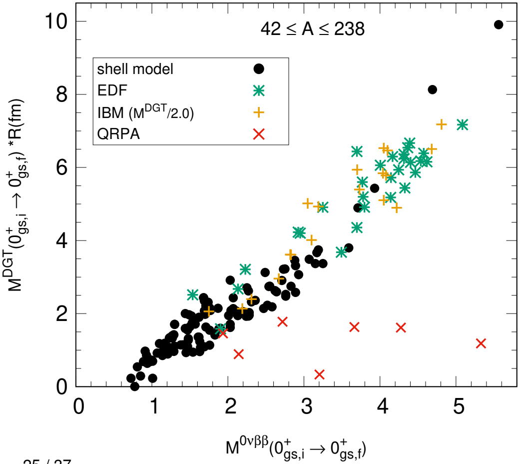
Shimizu, JM, Yako

PRL120 142502 (2018)



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)

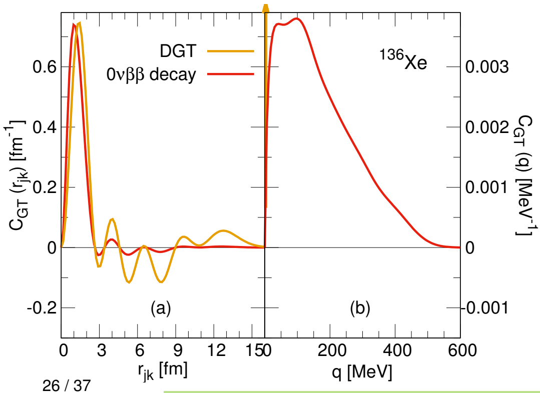
Common to shell model energy-density functionals interacting boson model, disagreement to QRPA

Experiments at RIKEN, INFN, RCNP? access DGT transitions

Short-range character of DGT, $0\nu\beta\beta$ decay

Correlation between DGT and $0\nu\beta\beta$ decay matrix elements explained by transition involving low-energy states combined with dominance of short distances between exchanged/decaying neutrons

Bogner et al. PRC86 064304 (2012)



$0\nu\beta\beta$ decay matrix element limited to shorter range

Short-range part dominant in double GT matrix element due to partial cancellation of mid- and long-range parts

Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako,
PRL120 142502 (2018)

Short-range character of DGT, $0\nu\beta\beta$ decay

Correlation between DGT and $0\nu\beta\beta$ decay matrix elements explained by transition involving low-energy states combined with dominance of short distances between exchanged/decaying neutrons

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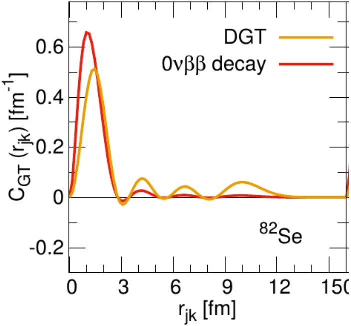
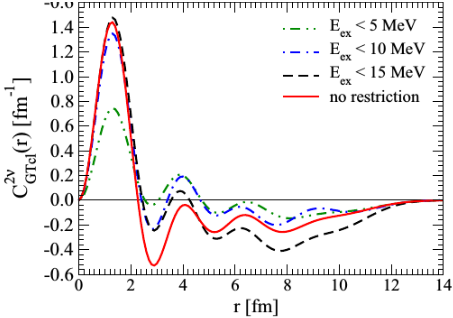


JM, JPSCP 23 012036 (2018)



Šimkovic et al. PRC 98 064325 (2019)

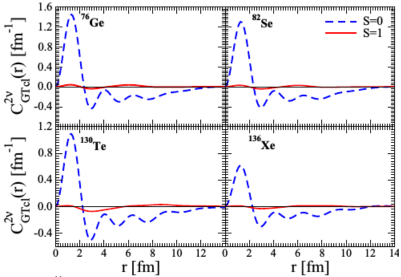
In contrast to NSM, long-range dominates QRPA DGT matrix elements

Contribution of $S = 1$ pairs to DGT NME

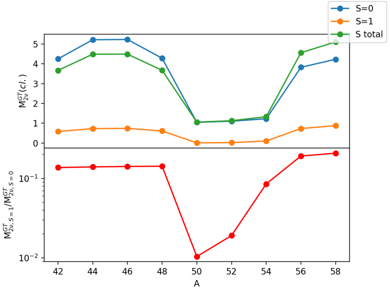
NMEs are dominated by $S = 0$ pairs

In DGT QRPA, $S = 1$ pair contributions extremely suppressed
lead to small $M^{DGT} = M^{DGT}_{S=0} + M^{DGT}_{S=1} = 4M^{DGT}_{S=1}$ (isospin conserved)

In contrast, nuclear shell model $M^{DGT}_{S=1}$ small but not negligible
even between seniority-zero states ($J = 0$ pairs, isospin not conserved)



Šimkovic et al. PRC 98 064325 (2019)

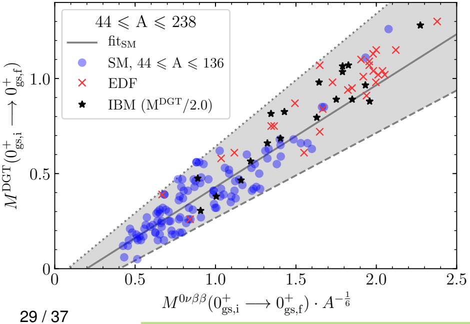


Linares, JM, in preparation

$0\nu\beta\beta$ decay NMEs in ET of β decay

Effective theory of β decay can calculate DGT with uncertainties
(similar to calculation of $2\nu\beta\beta$, no energy denominator)
DGT vs 0nbb correlation $\Rightarrow$ predict $0\nu\beta\beta$ NMEs with uncertainties

Because ET couplings fitted to β decay and GT strengths
correct shell model DGT NMEs in correlation
by "quenching" factor for these observables: $q = 0.42 - 0.65$



As a result, ET $0\nu\beta\beta$ NMEs
^{76}Ge: $M^{0\nu} = 0.3 - 1.5$
^{82}Se: $M^{0\nu} = 0.3 - 1.6$

smaller than most calculations

large uncertainty:
LO in ET, fit, "quenching"

Brase, Coello Pérez, JM, Schwenk
in preparation

Outline

$0\nu\beta\beta$ decay: huge potential, great challenge

Nuclear structure data as test of $0\nu\beta\beta$ calculations

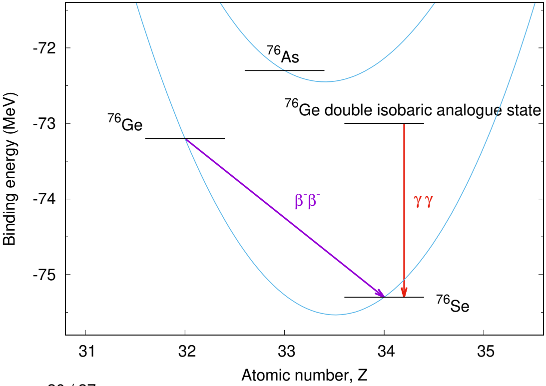
Double Gamow-Teller transitions and $0\nu\beta\beta$ decay

$\gamma\gamma$ transitions and $0\nu\beta\beta$ 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

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



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
arXiv:2102.11101

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)

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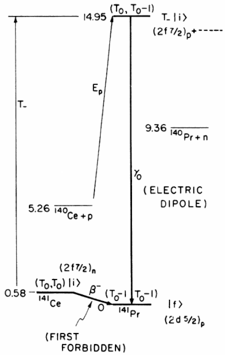
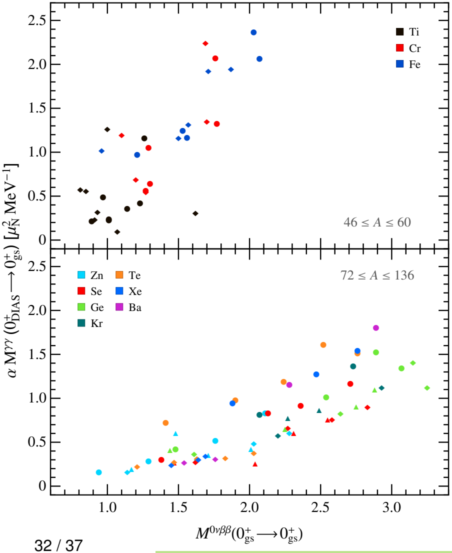


Correlation between $M1M1$ and $0\nu\beta\beta$ NMEs



Good correlation between $M1M1$ and $0\nu\beta\beta$ NMEs!

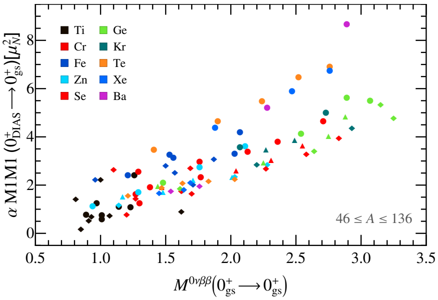
Valid across the nuclear chart for the nuclear shell model

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

The correlation is slightly different for lighter nuclei: effect of energy denominator

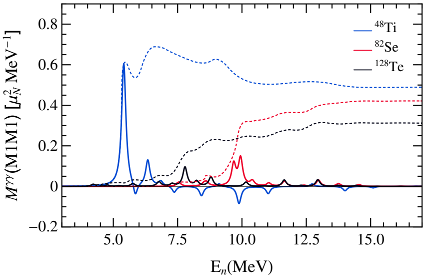
Romeo, JM, Peña-Garay arXiv:2102.11101

Intermediate states of the $M1M1$ transition



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

Romeo, JM, Peña-Garay arXiv:2102.11101



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

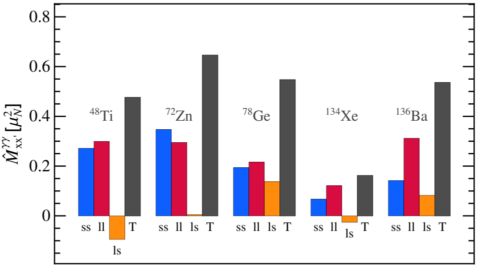
One or few intermediate states typically dominate the transition

Spin, angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{ss} + \hat{M}_{ll} + \hat{M}_{ls}$$

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

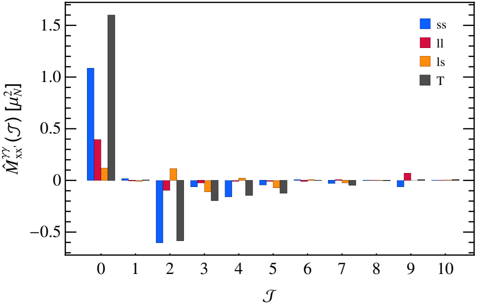
Romeo, JM, Peña-Garay
arXiv:2102.11101

Total angular momentum decomposition

The numerator NME can be decomposed into

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

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

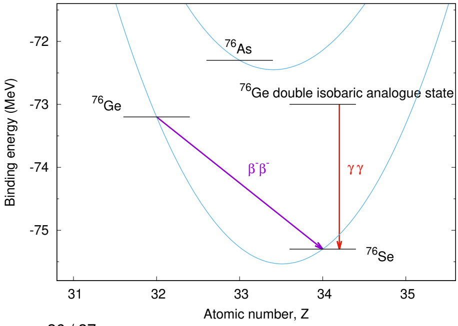
Romeo, JM, Peña-Garay
arXiv:2102.11101

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

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

Valiente-Dobón, Romeo et al., in prep

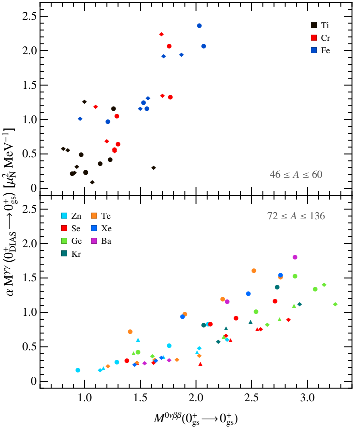
Summary

Calculations of $0\nu\beta\beta$ NMEs
challenge nuclear many-body methods

$0\nu\beta\beta$ searches demand reliable NMEs
nuclear structure measurements can
inform us on their value

Double Gamow-Teller transitions
very good correlation with $0\nu\beta\beta$ NMEs
potentially accessible in charge
exchange experiments

Electromagnetic $M1M1$ decay
of the DIAS of the initial $\beta\beta$ nucleus
good correlation to $0\nu\beta\beta$ NMEs
feasibility of measurements in progress



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