Nuclear structure observables to shed light on neutrinoless double-beta decay

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Investigación Programa Ramón y Cajal

ICCUB

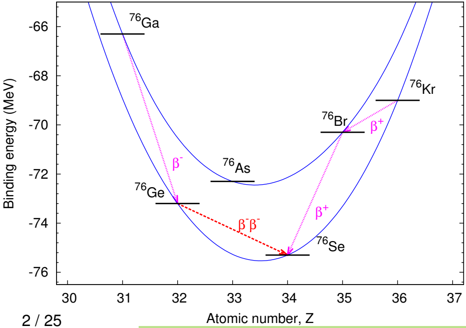
$\beta\beta$ decay

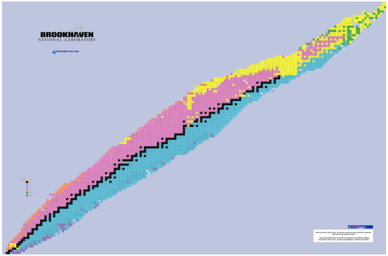
Second order process in the weak interaction

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

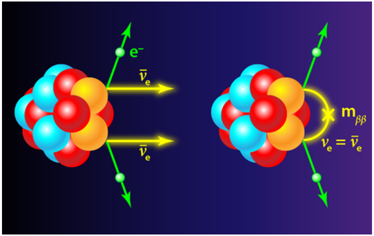




Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

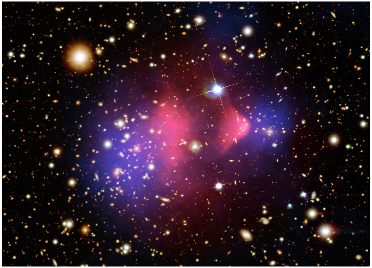
Nuclear structure physics encoded in nuclear matrix elements key to plan, fully exploit experiments



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

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

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



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

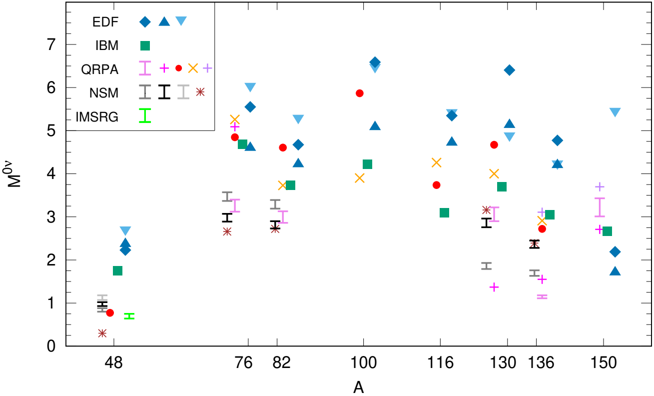
$0\nu\beta\beta$ decay nuclear matrix elements

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

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

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

$H(r) =$ neutrino potential

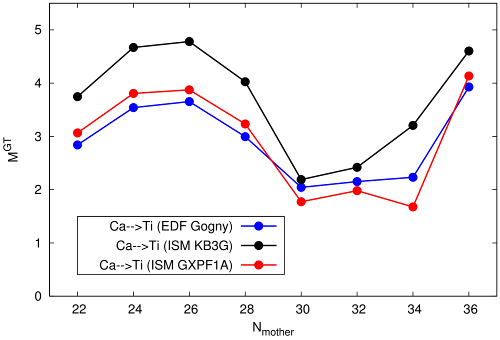


Engel, JM, Rep. Prog. Phys. 80 046301 (2017), updated

$0\nu\beta\beta$ decay without correlations

Non-realistic spherical (uncorrelated) mother and daughter nuclei:

- Shell model (SM): zero seniority, neutron and proton $J = 0$ pairs
- Energy density functional (EDF): only spherical contributions



In contrast to full (correlated) calculation SM and EDF NMEs agree!

NME scale set by pairing interaction

JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)

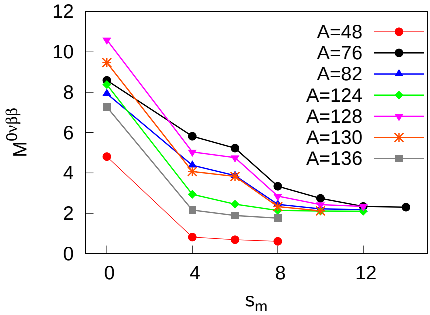
NME follows generalized seniority model:

$M_{GT}^{0\nu\beta\beta} \simeq \alpha_\pi \alpha_\nu \sqrt{N_\pi + 1}\sqrt{\Omega_\pi - N_\pi}\sqrt{N_\nu}\sqrt{\Omega_\nu - N_\nu + 1}$, Barea, Iachello PRC79 044301(2009)

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

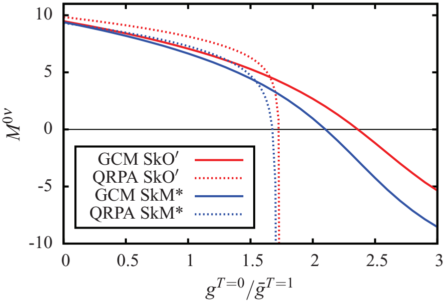
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing,
but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix element value

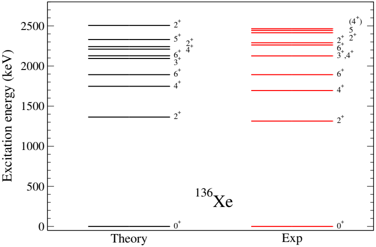


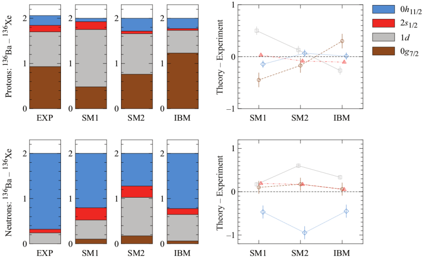
Hinohara, Engel PRC90 031301 (2014)

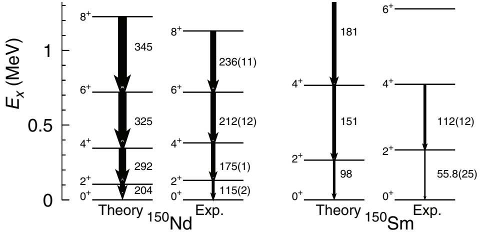
Related to approximate $SU(4)$ symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator

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)

...

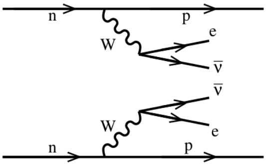
Vietze et al. PRD91 043520 (2015)

Two-neutrino $\beta\beta$ decay, 2νECEC

$2\nu\beta\beta$ decay share initial, final states, operator structure ($\sigma\tau$) 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 → ^{48}Ti	0.047 ± 0.003	0.74	0.047	kb3
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.048	kb3g
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.065	gxpf1
^{76}Ge → ^{76}Se	0.140 ± 0.005	0.60	0.116	gcn28:50
^{76}Ge → ^{76}Se	0.140 ± 0.005	0.60	0.120	jun45
^{82}Se → ^{82}Kr	0.098 ± 0.004	0.60	0.126	gcn28:50
^{82}Se → ^{82}Kr	0.098 ± 0.004	0.60	0.124	jun45
^{128}Te → ^{128}Xe	0.049 ± 0.006	0.57	0.059	gcn50:82
^{130}Te → ^{130}Xe	0.034 ± 0.003	0.57	0.043	gcn50:82
^{136}Xe → ^{136}Ba	0.019 ± 0.002	0.45	0.025	gcn50:82

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

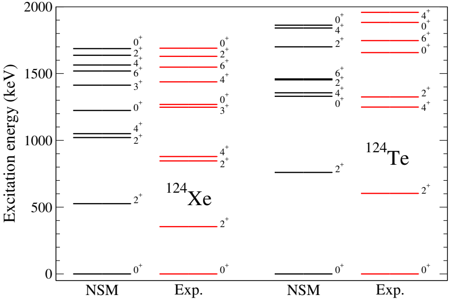
^{124}Xe 2ν double electron-capture search by XMASS, XENON1T experiments

Shell model configuration space

For xenon, use ^{100}Sn core
with $0g_{7/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$, $0h_{11/2}$ orbitals for neutrons and protons

$^{124}_{54}$Xe$_{70}$ $\rightarrow$ $^{124}_{52}$Te$_{72}$ demanding: almost mid-shell neutron configurations, truncated configuration space:

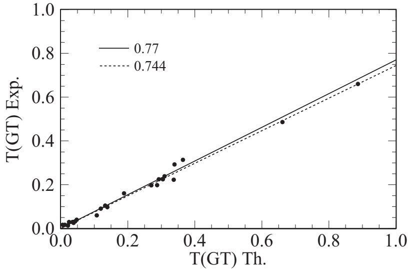
- Maximum two-nucleon excitations to $2s_{1/2}$, $1d_{3/2}$, $0h_{11/2}$ orbitals
- Like above neutron $0g_{7/2}$ fully occupied no restriction on protons
- Like above neutron $1d_{5/2}$ fully occupied no restriction on protons



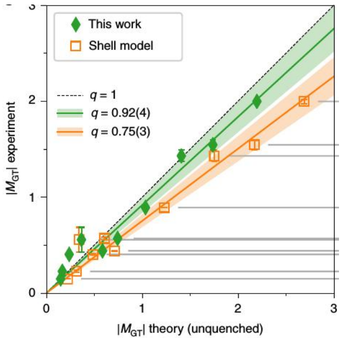
Combine results of the approximate shell model diagonalizations

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)

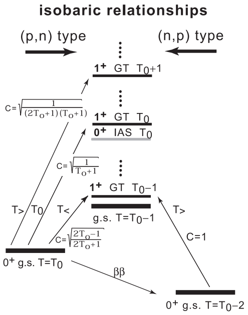
$$\langle F|\sum_i [g_A\,\boldsymbol{\sigma}_i\tau_i^-]^{\text{eff}}\,|I\rangle\,,\quad [\boldsymbol{\sigma}_i\tau]^{\text{eff}} \approx 0.7\boldsymbol{\sigma}_i\tau$$

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

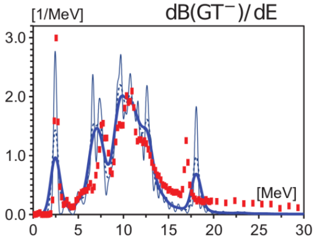
Ab initio calculations including meson-exchange currents do not need any “quenching”

Gamow-Teller strength distributions

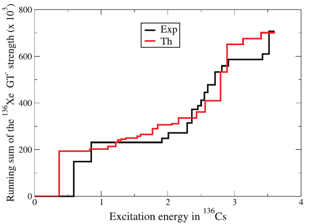
GT strength distribution complements β-decay beyond Q-value region



Frekers et al.
NPA916 219 (2013)



Iwata et al. JPSCP6 3057 (2015)



Caurier et al. PLB711 62 (2012)

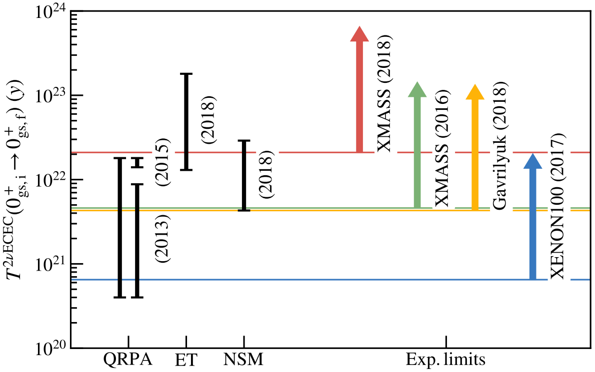
$$\frac{d\sigma}{d\Omega}(\theta=0) \propto \sum \boldsymbol{\sigma}_i \tau^{\pm}$$

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

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 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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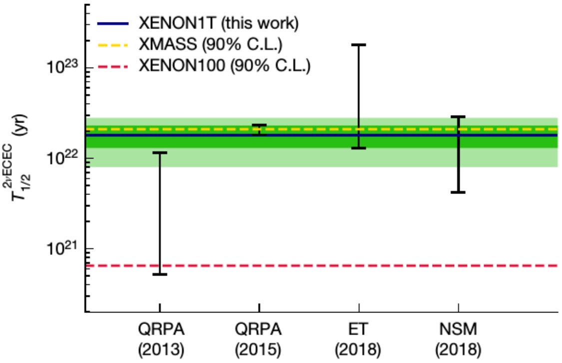


Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

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

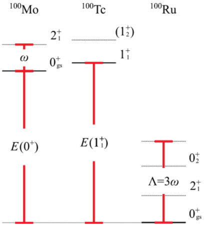
XENON1T
Nature 568 532 (2019)

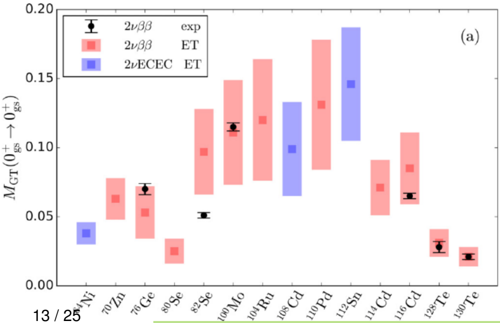
Shell model, QRPA and Effective theory (ET) predictions
good agreement with XENON1T measurement of 2νECEC!

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

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

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

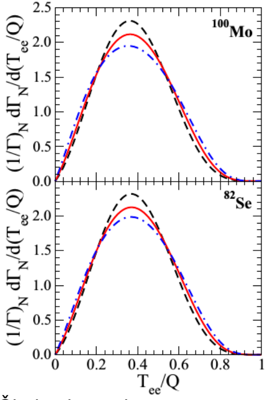
$$M^{2\nu}_{GT3} = \sum_j \frac{4\langle 0^+_f | \sum_l \boldsymbol{\sigma}_l \tau^-_l | 1^+_j \rangle \langle 1^+_j | \sum_l \boldsymbol{\sigma}_l \tau^-_l | 0^+_i \rangle}{\Delta^3},$$

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

Electron differential decay rate:

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

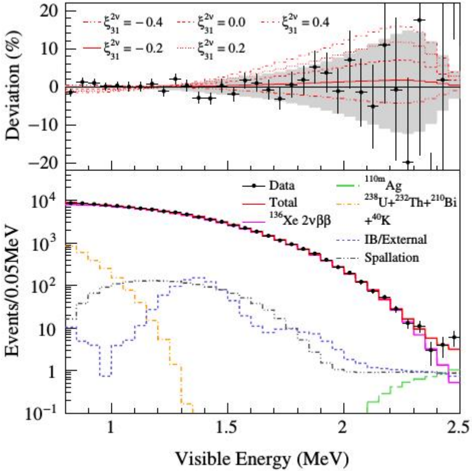
Exp. sensitivity to $\xi^{2\nu}_{31} = M^{2\nu}_{GT-3}/M^{2\nu}_{GT}$



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

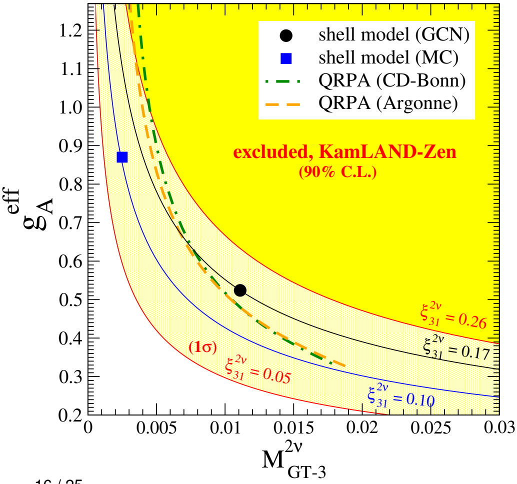


KamLAND-Zen $2\nu\beta\beta$ analysis excludes larger values of $\xi^{2\nu}_{31}$

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 ("queching")

$\xi_{31}^{2\nu}$ measurement test theoretical models

Theory-experiment work with KamLAND-Zen collaboration

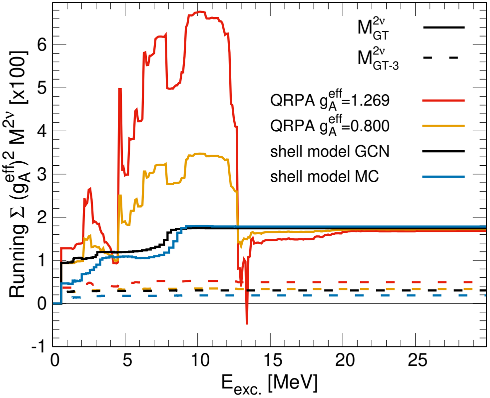
Theory: JM, Dvornicky, Šimkovic

Shell model $\xi_{31}^{2\nu}$ predictions consistent with 90% C.L. limit

KamLAND-Zen et al.
PRL122 192501 (2019)

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

Measurements of $\beta\beta$ decay spectra can test calculations
with different matrix element as function of energy of intermediate state



Qualitative very different
shell model vs QRPA

QRPA also quite different
between different g_A^{eff} values
(or diff. isoscalar pairing g_{pp})

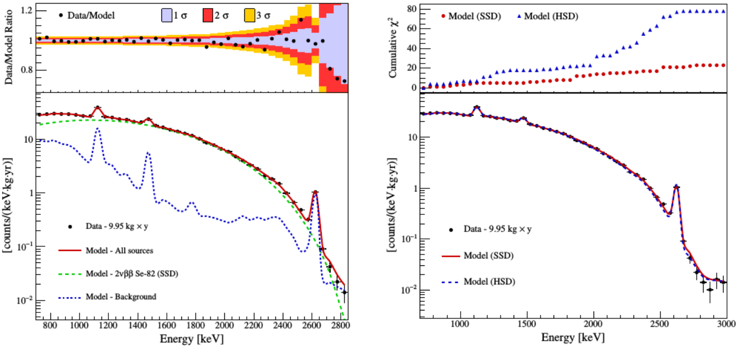
Smaller QRPA g_A^{eff} preferred
in some β-decay studies
Faessler et al.
JPG 35 075104 (2008)

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

Single-state dominance in $2\nu\beta\beta$ decays

Recent CUPID-0 measurement of single-state dominance of lowest-lying intermediate ^{82}Br 1^+ state in $^{82}\text{Se} \rightarrow {}^{82}\text{Kr} + 2\bar{\nu} + 2e$ decay

CUPID-0, PRL123 262501 (2019)



Single-state dominance in ^{82}Se $2\nu\beta\beta$ decay confirmed by NEMO-3

Not predicted by any theoretical calculation

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

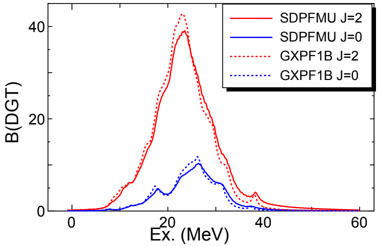
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

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)



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

Double Gamow-Teller distribution and pairing

Study the sensitivity of Double GT distribution to pairing correlations

Add/remove pairing

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

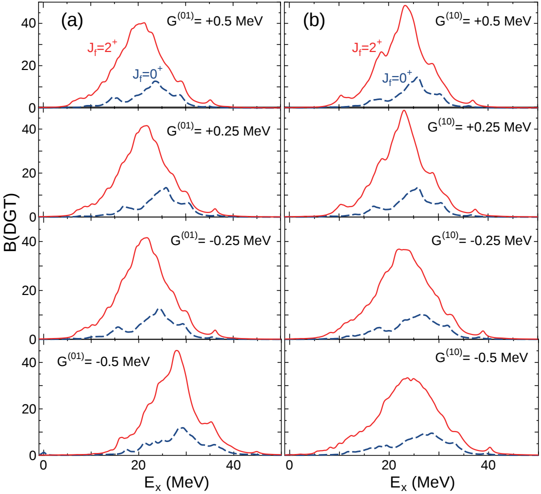
like-particle (T=1) or proton-neutron (T=0)

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

DGT resonance width probes isoscalar pairing

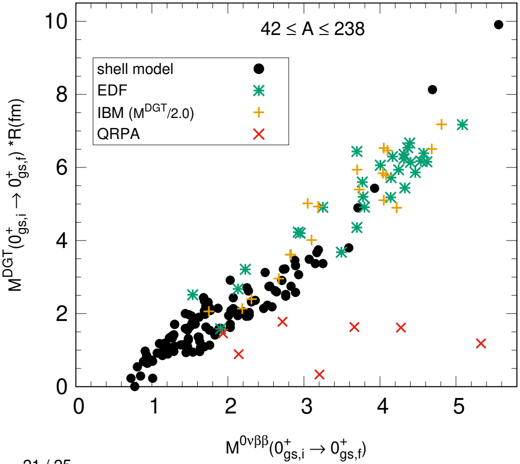
Shimizu, JM, Yako

PRL120 142502 (2018)



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

Double GT transition to ground state $M^{\rm DGT} = \langle F_{gs} || [\sum_i \boldsymbol{\sigma}_i \tau_i^- \times \sum_j \boldsymbol{\sigma}_j \tau_j^-]^0 || I_{gs} \rangle|^2$
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)

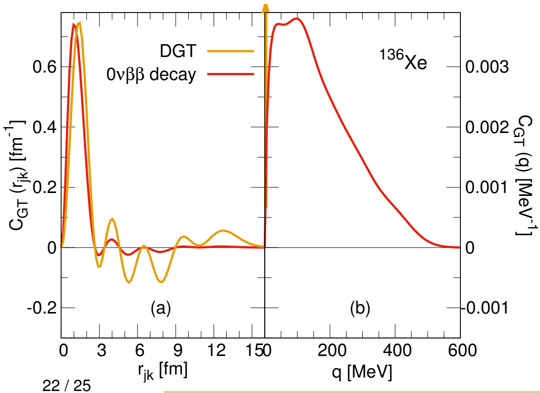
Common to shell model energy-density functionals interacting boson model, disagreement to QRPA

Experiments at RIKEN, INFN Catania may 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

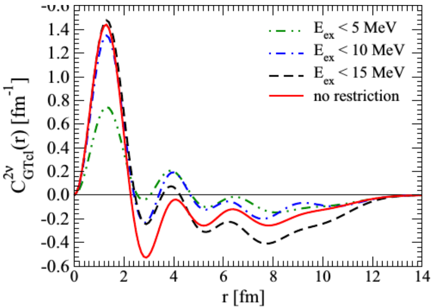
Short-range part dominant in double GT matrix element due to partial cancellation of mid- and long-range parts

Long-range part dominant in QRPA DGT matrix elements

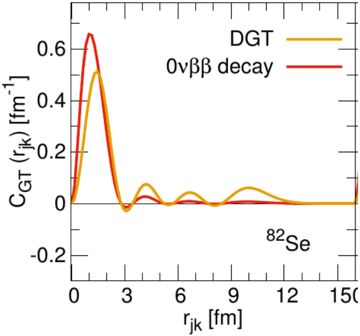
Shimizu, JM, Yako, PRL120 142502 (2018)

Radial density of $2\nu\beta\beta$ in closure (double GT)

Qualitatively different behaviour shell model vs QRPA
in $2\nu\beta\beta$ with closure approximation, $\sim \boldsymbol{\sigma\sigma}\,\tau\tau$ (double GT transitions)



Šimkovic, Smetana, Vogel
PRC 98 064325 (2019)



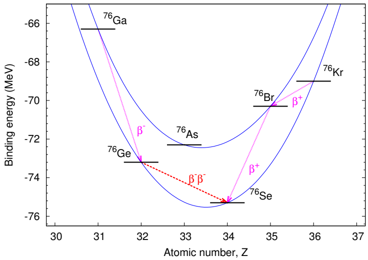
JM, JPSCP 23 012036 (2018)

Reduction (QRPA) or not (shell model) as function of E_{ex} of $M^{2\nu}$
translates into qualitatively different radial "density" of matrix element

$0\nu\beta\beta$ and $\gamma\gamma$ decays

Explore correlation between $0\nu\beta\beta$ and $\gamma\gamma$ decays, focused on double-M1 transitions

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



Similar initial and final states both in same nucleus (IAS) in electromagnetic transition

M1 and GT operators very similar when M1 dominated by physics of spin (small effect of orbital part)

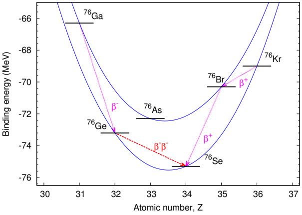
Stay tuned!

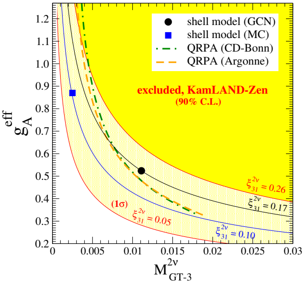
B. Romeo, JM, C. Peña-Garay, in progress

Summary

Measurements of 2νECEC of ^{124}Xe
and high-statistics electron spetrum of ^{136}Xe
stringent tests of $\beta\beta$ calculations
that inform predictions of $0\nu\beta\beta$ decay

- Shell model can be predictive
  when correcting deficiencies
  (“quenching”)
  based on β-decay data
- Electron spectra in $2\nu\beta\beta$ decay
  additional test of nuclear calculations
- Double Gamow-Teller transitions
  2nd-order electromagnetic transitions (?)
  potential opportunity to obtain information
  from $0\nu\beta\beta$ nuclear matrix elements





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Thanks!