Nuclear structure for neutrinoless double-beta decay

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13th International Spring Seminar on Nuclear Physics:
“Perspectives and Challenges in Nuclear Structure
after 70 Years of Shell Model”

Sant’Angelo d’Ischia, 19$^{\text{th}}$ May 2022

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

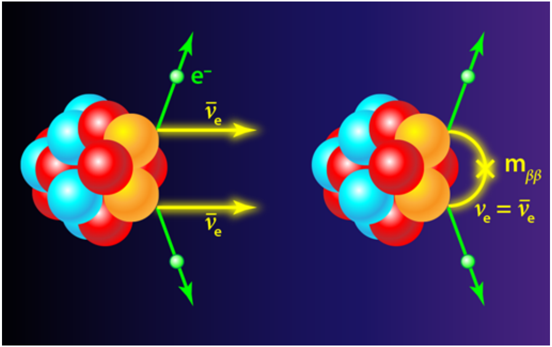
Lepton number is conserved
in all processes observed:

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

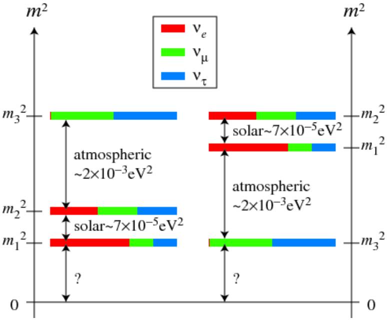
Agostini, Benato, Detwiler, JM, Vissani, arXiv:2202.01787

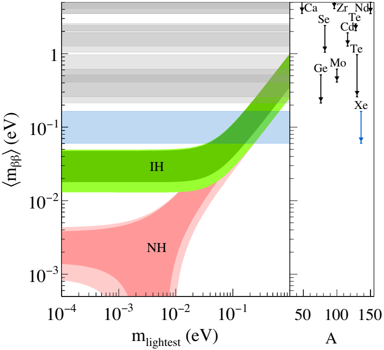


Next generation experiments: inverted hierarchy

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

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

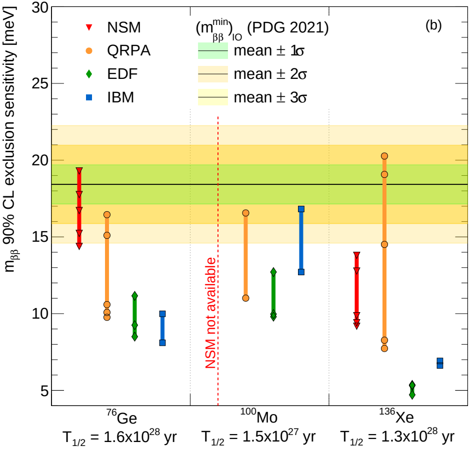




KamLAND-Zen, PRL117 082503(2016)

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

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



Agostini, Benato, Detwiler, JM, Vissani
Phys. Rev. C 104 L042501 (2021)

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

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

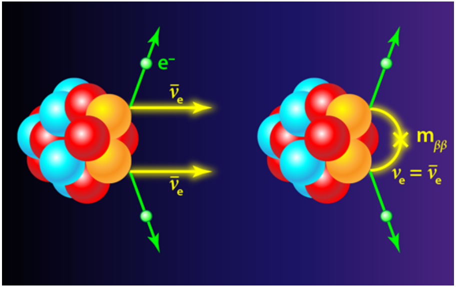
Uncertainty needs to be reduced!

Nuclear matrix elements

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

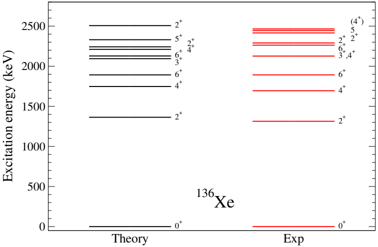
$$\langle \text{Final} \,|\mathcal{L}_{\text{leptons}-\text{nucleons}}|\, \text{Initial} \rangle = \langle \text{Final} \,|\int dx\, j^{\mu}(x) J_{\mu}(x)\,|\, \text{Initial} \rangle$$

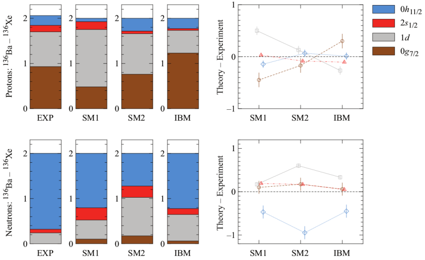
- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  QMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD

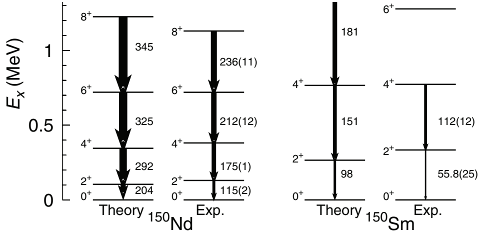


Tests of nuclear structure

Spectroscopy well described: masses, spectra, transitions, knockout...







Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Szwec et al., PRC94 054314 (2016)

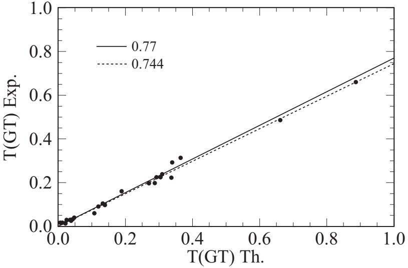
Rodríguez et al. PRL105 252503 (2010)

...

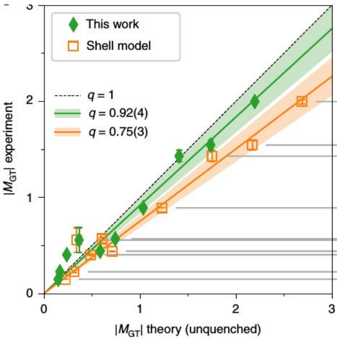
Vietze et al. PRD91 043520 (2015)

β–decay Gamow-Teller transitions: "quenching"

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



Martinez-Pinedo et al. PRC53 2602(1996)



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

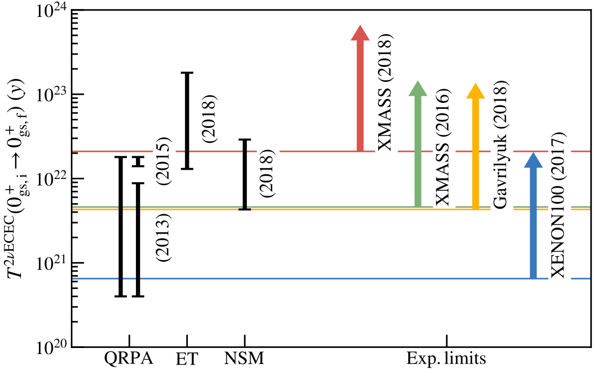
$$\langle F|\sum_i [g_A\,\boldsymbol{\sigma}_i\tau_i^-]^{\text{eff}}\,|I\rangle\,,\quad [\boldsymbol{\sigma}_i\tau]^{\text{eff}} \approx 0.7\boldsymbol{\sigma}_i\tau$$

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

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

Two-neutrino ECEC of ^{124}Xe

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



Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

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

Shell model, QRPA and Effective theory (ET) predictions
suggest experimental detection close to XMASS 2018 limit

Two-neutrino ECEC of ^{124}Xe

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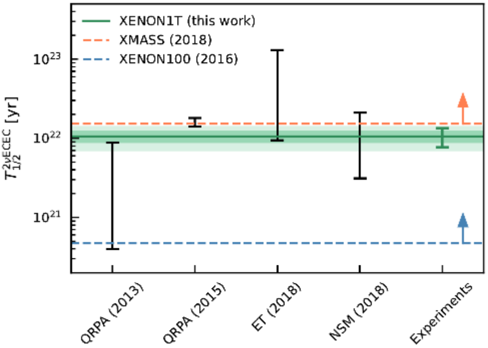


Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

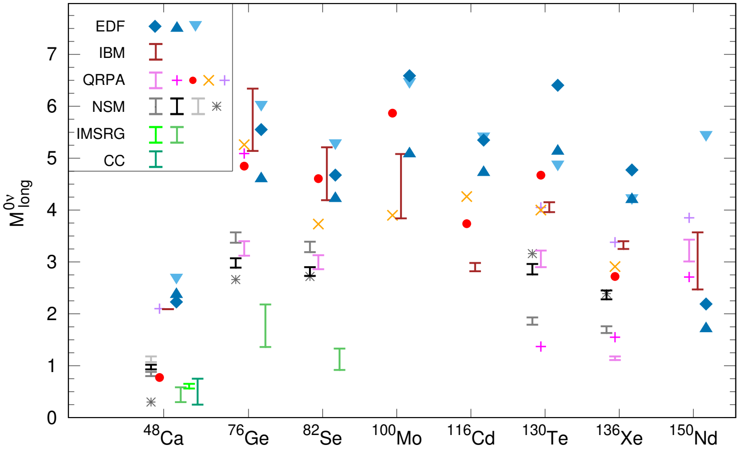
Coello Pérez, JM, Schwenk
PLB 797 134885 (2019)

XENON1T
Nature 568 532 (2019)
arXiv:2205.04158

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

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

Large difference in nuclear matrix element calculations: factor ~ 3

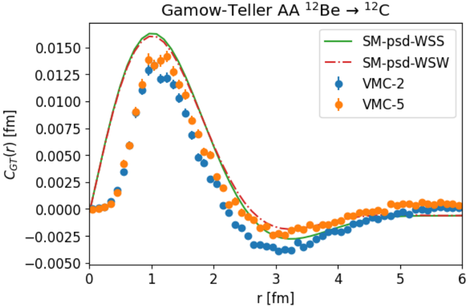


Agostini, Benato, Detwiler, JM, Vissani, arXiv:2202.01787

Shell model vs quantum Monte Carlo: correlations

Compare $\beta\beta$ transition densities in
nuclear shell model and quantum Monte Carlo calculations in light nuclei

Generally good agreement at long distances,
short-range correlations missing in shell model



Weiss, Lovato, JM, Soriano, Wiringa, arXiv:2112:08146

Similar findings in Wang et al. PLB 798 134974 (2019)

Generalized contact formalism (GCF)

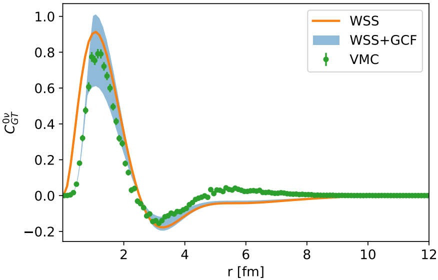
Generalized contact formalism Weiss, Bazak, Barnea PRL 114 012501 (2015)

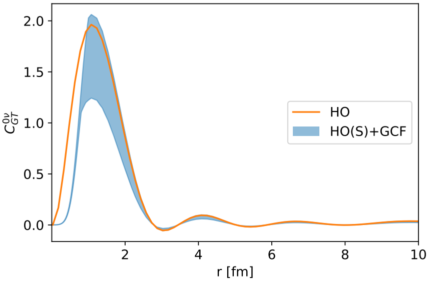
Separation of scales: wf, transition density factorize for two nearby nucleons

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

with $\varphi(r)$ the solution of the two-nucleon Schrödinger equation

The contact $C^0(f,i) = \frac{A(A-1)}{2}\langle A^{\alpha}(f)|A^{\beta}(i)\rangle$ is model dependent
but for two nuclei the ratio $C^0_{pp,nn}(X)/C^0_{pp,nn}(Y)$ relatively model independent:
combine QMC calculation in light nuclei with two shell model calculations:

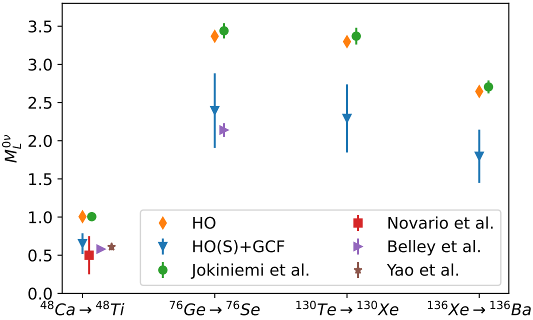




Shell model + Generalized contact formalism: NMEs

GCF builds QMC short-range correlations to shell model transitions densities can be extended to heavy nuclei where shell model calculations are possible

Weiss et al. arXiv:2112:08146



Short-range correlations included by GCF reduce $0\nu\beta\beta$ NMEs moderately

$\sim$ 30% reduction in general consistent with ab initio NMEs in ^{48}Ca, ^{76}Ge

Good agreement in benchmark NMEs in light nuclei with ab initio calculations

Light-neutrino exchange: contact operator

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

Contribution of high-energy neutrinos

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

Cirigliano et al. PRL120 202001(2018)

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

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

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

Lattice QCD calculations can obtain value of g_ν^{NN}

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

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

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

Contact matrix element: relative impact

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

Assume $g_\nu^{\text{NN}} \sim 1\text{fm}^2$

Cirigliano et al.
PRC100 055504 (2019)

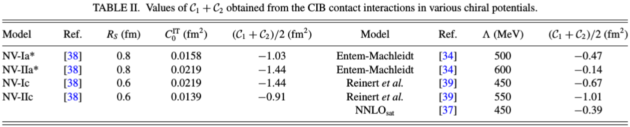
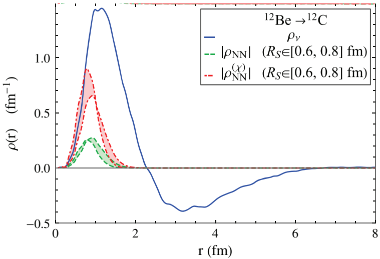


TABLE II. Values of $\mathcal{C}_1 + \mathcal{C}_2$ obtained from the CIB contact interactions in various chiral potentials.

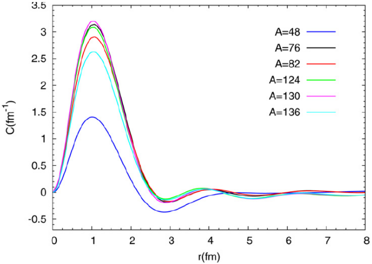
Model	Ref.	R_S (fm)	C_0^{IT} (fm^2)	$(\mathcal{C}_1 + \mathcal{C}_2)/2$ (fm^2)	Model	Ref.	Λ (MeV)	$(\mathcal{C}_1 + \mathcal{C}_2)/2$ (fm^2)
NV-Ia*	[38]	0.8	0.0158	−1.03	Entem-Machleidt	[34]	500	−0.47
NV-IIa*	[38]	0.8	0.0219	−1.44	Entem-Machleidt	[34]	600	−0.14
NV-Ic	[38]	0.6	0.0219	−1.44	Reinert *et al.*	[39]	450	−0.67
NV-IIc	[38]	0.6	0.0139	−0.91	Reinert *et al.*	[39]	550	−1.01
					NNLO$_{\text{sat}}$	[37]	450	−0.39

$\sim$ 75% correction for QMC ^{12}Be NME

In heavy nuclei, less severe cancellation of dominant $M^{0\nu}$?



Cirigliano et al. PRL120 202001(2018)



JM et al. NPA818 139 (2009)

Contact operator for NME calculations in heavy nuclei

Calculate $M^{0\nu}_{\text{short}}$ in heavy nuclei to see impact in nuclei used in $0\nu\beta\beta$ searches

Use g_ν^{NN} and Λ values from
charge independence breaking (CIB) contact term of chiral EFT potentials
assume same value for two CIB couplings $\mathcal{C}_1 = \mathcal{C}_2$

$g_\nu^{\text{NN}}(\text{fm}^2)$	Λ (MeV)	
-0.67	450	Reiner et al. Eur. Phys. J. A 54 86 (2018)
-1.01	550	"
-1.44	465	Piarulli et al. Phys. Rev. C 94 054007 (2016)
-0.91	465	"
-1.44	349	"
-1.03	349	"

Consider Gaussian regulators: $h_s = 2g_\nu^{\text{NN}} g(p/\Lambda)$

Perform calculations with the nuclear shell model:
^{48}Ca, ^{76}Ge, ^{82}Se, ^{124}Sn, ^{128}Te, ^{130}Te and ^{136}Xe

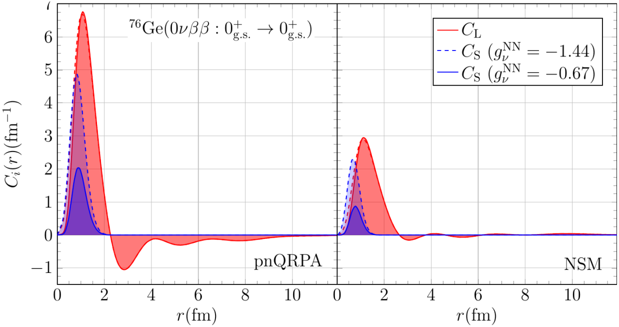
and the quasiparticle random-phase approximation method (QRPA):
^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{128}Te, ^{130}Te and ^{136}Xe

Long and short-range NME in heavy nuclei

Relatively stable contribution of new term M_S/M_L:

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

consistent with 43% effect in IM-GCM for ^{48}Ca
using synthetic data on $nn \to pp + ee$ decay Wirth et al. PRL127 242502 (2021)



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

Uncertainty dominated by coupling g_ν^{NN}

Relative impact of new short-range contribution

In transitions with larger cancellation from tail in NME distribution new short-range term becomes relatively more important

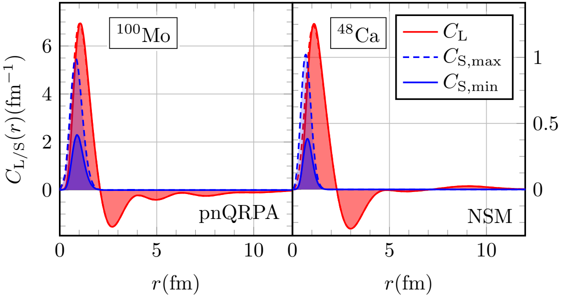
Nuclear shell model: ^{48}Ca with 25% – 65% contribution

consistent with Wirth et al. PRL127 242502 (2021)

QRPA: ^{100}Mo with 50% – 100% contribution

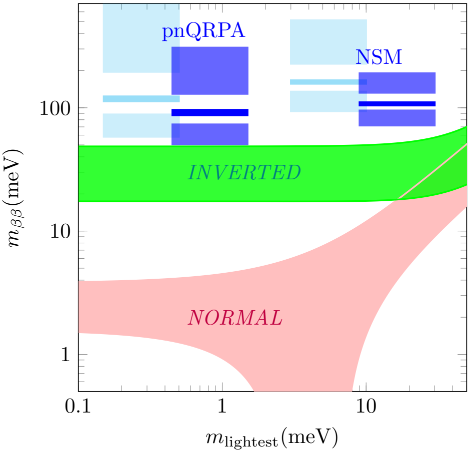
due to negative contributions of 1^+ intermediate states

explains smaller effect than QMC calculations in very light nuclei and larger contribution in QRPA than nuclear shell model



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

Impact on tests of inverted hierarchy of neutrino mass



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

Assuming these g_ν^{NN} values significant impact on current $0\nu\beta\beta$ limits on neutrino mass parameter $m_{\beta\beta}$

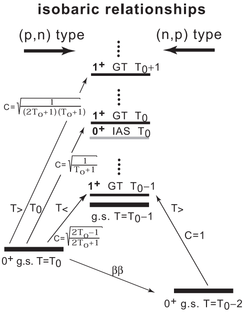
Ab initio determination using synthetic $nn \to pp + ee$ data suggests constructive sign between M_L and M_S

Wirth et al. PRL127 242502 (2021)

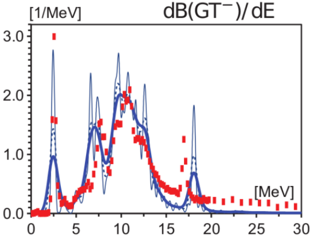
Short-range matrix element may roughly compensate effect of missing correlations in shell model, QRPA NME calculations

Gamow-Teller strengths and β decays

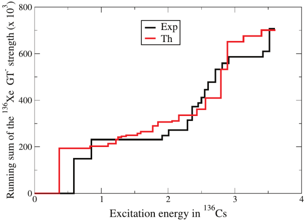
GT strength distribution complements β-decay beyond Q-value region



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

Double Gamow-Teller strengths and $\beta\beta$ decay

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

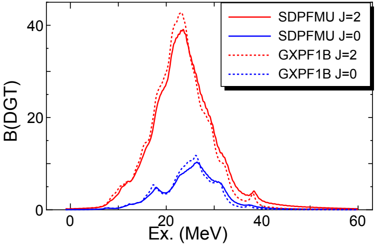
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

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

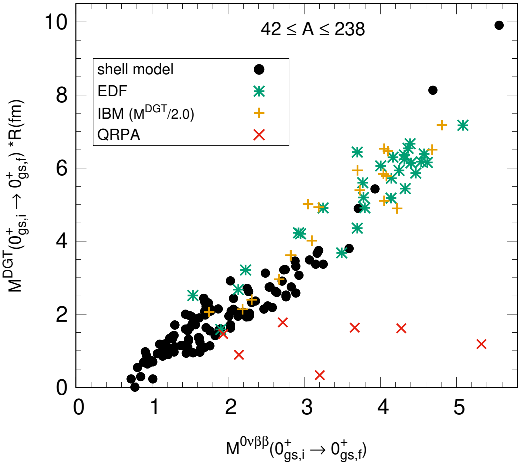
Shimizu, JM, Yako, PRL120 142502 (2018)



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

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



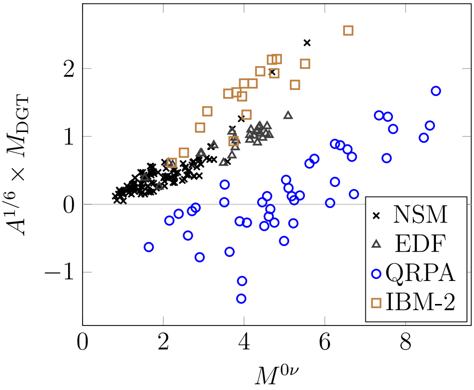
Double Gamow-Teller correlation with $0\nu\beta\beta$ decay holds across nuclear chart
Shimizu, JM, Yako
PRL120 142502 (2018)

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

Experiments at RIKEN, INFN, RCNP? access DGT transitions

Correlation of $0\nu\beta\beta$ decay to DGT in QRPA

In QRPA, g_{pp} parameter
typically fitted to reproduce $2\nu\beta\beta$ half-life of measured transitions
but actually some tension between g_{pp} values to reproduce single-β decays
Faessler et al., J. Phys. G 35, 075104 (2008)



Jokiniemi, JM, in preparation

Perform QRPA calculations with range of $g_{pp} = (0.6 - 0.9)$

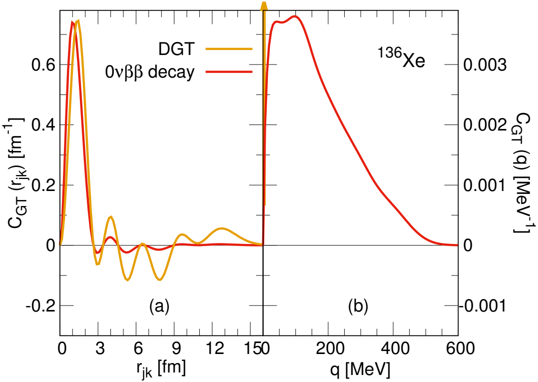
Correlation between
DGT and $0\nu\beta\beta$ NMEs!
but different than for
other many-body methods

Partially caused by relevance of
$J > 1$ intermediate states in QRPA
compared to eg shell model
Ejiri et al. Phys. Rept. 797 1 (2019)
Horoi et al, PRC 93, 044334 (2016)

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)

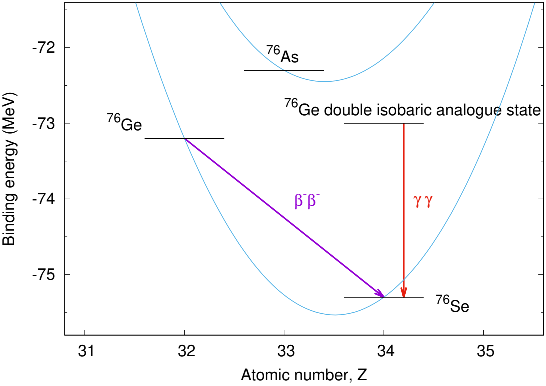
However, ab initio study of DGT vs $0\nu\beta\beta$ NME finds weaker correlation:

Yao et al. arXiv:2204.12971

$\gamma\gamma$ 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

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



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
PLB 827 136965 (2022)

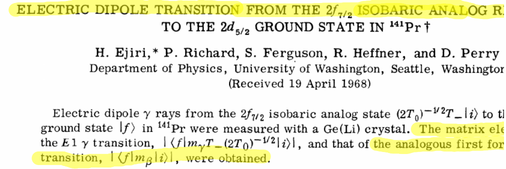
β decays and γ transitions from IAS

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...

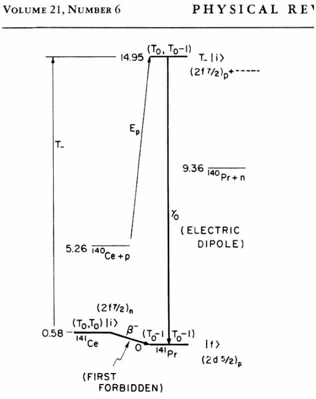


ELECTRIC DIPOLE TRANSITION FROM THE $2f_{7/2}$ ISOBARIC ANALOG R
TO THE $2d_{5/2}$ GROUND STATE IN ^{141}Pr †

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

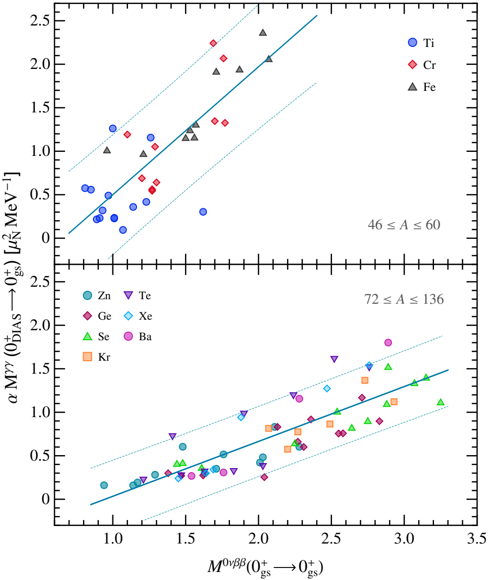
Electric dipole γ rays from the $2f_{7/2}$ isobaric analog state $(2T_0)^{-1/2}T_-|i\rangle$ to tl
ground state $|f\rangle$ in ^{141}Pr were measured with a Ge(Li) crystal. The matrix ele
the $E1$ γ transition, $|\langle f|m_\gamma T_-(2T_0)^{-1/2}|i\rangle|$, and that of the analogous first for
transition,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

PRL 21 373 (1968)



VOLUME 21, NUMBER 6 PHYSICAL RE

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



Good correlation between $M1M1$ same-energy photons 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
PLB 827 136965 (2022)

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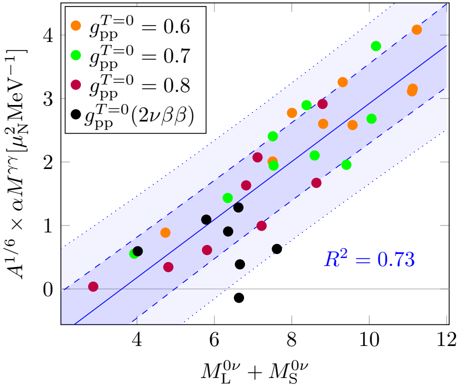

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Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Correlation also holds for total $M_L + M_S$ NME!

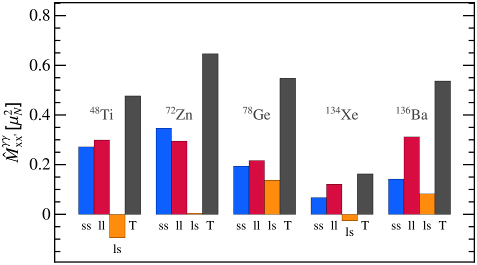
Jokiniemi et al. in preparation

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

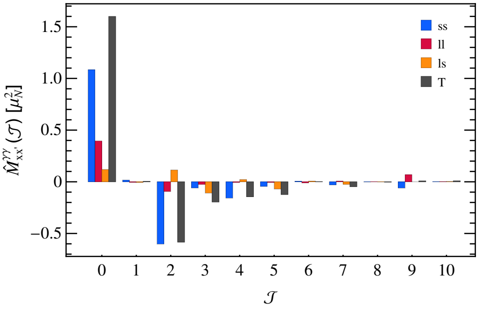
Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

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:

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

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

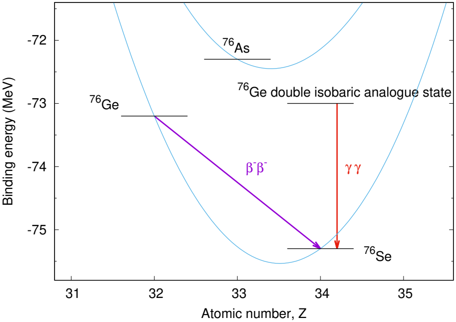
Romeo et al. PLB 827 136965 (2022)

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

Improved short-range correlations
using generalized contact formalism
reduce NMEs in line with ab initio results

Leading order short-range matrix element
can vary significantly overall NME value
most likely increases $0\nu\beta\beta$ rate

Double Gamow-Teller transitions,
electromagnetic *M*1*M*1 decay of DIAS
good correlation with $0\nu\beta\beta$ NMEs
may be exploited to gain insight on NMEs