Two body (meson exchange) currents and Gamow-Teller quenching

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東京大学
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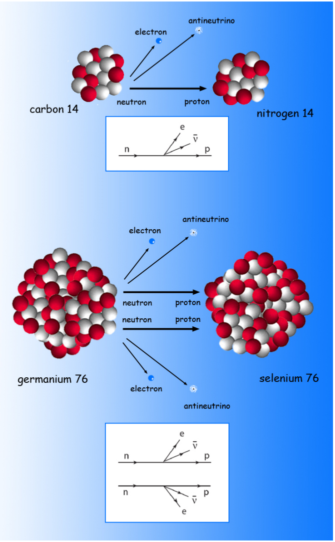
Weak transitions in nuclei

β and $\beta\beta$ decay processes, Weak interaction

$$\mathcal{L}_W = \frac{G_F}{\sqrt{2}} \left(j_{L\mu} J_L^{\mu\dagger} \right) + H.c.$$

$j_{L\mu}$ leptonic current: electron, neutrino

$J_L^{\mu\dagger}$ hadronic current: quarks → nucleons



In nuclei (non-relativistic), β decay is

$$\langle F | \sum_i g_V \, \tau_i^- + g_A \, \boldsymbol{\sigma}_i \tau_i^- \, | I \rangle$$

Fermi and Gamow-Teller transitions

corrections (forbidden transitions)
expansion of the leptonic current

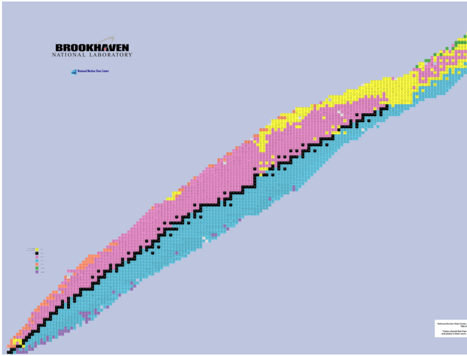
Matrix elements

Nuclear matrix elements for weak transitions

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

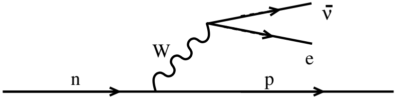
- Nuclear structure calculation of the initial and final states:
  Ab initio, shell model,
  energy density functional...

- Lepton-nucleus interaction:
  Evaluate (non-perturbative)
  hadronic currents inside nucleus:
  phenomenology, effective theory



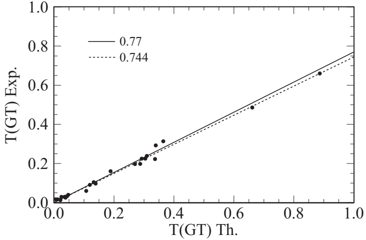
Gamow-Teller transitions

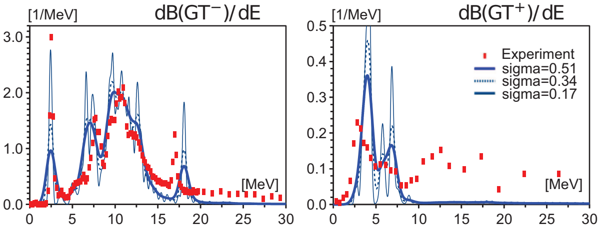
Single-β, Gamow-Teller (GT) transitions well described by theory...



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

...but need to “quench“ GT operator





Martinez-Pinedo et al.

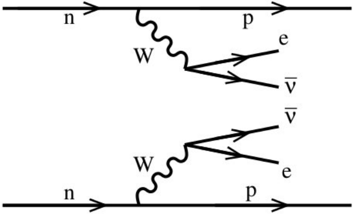
PRC 53 2602 (1996)

Iwata et al.

JPSCP 6 03057 (2015)

Double–Gamow-Teller transitions

$2\nu\beta\beta$ decays also well described with "quenched" GT operator



Caurier, Nowacki, Poves PLB 711 62 (2012)

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

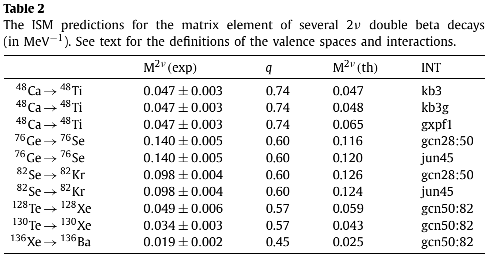


Table 2
The ISM predictions for the matrix element of several 2ν double beta decays (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
^{48}Ca $\to$ ^{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

This puzzle has been the target of many theoretical efforts:

Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...

Anything missing in the transition operator or in many-body approach?

Shell model nuclear structure

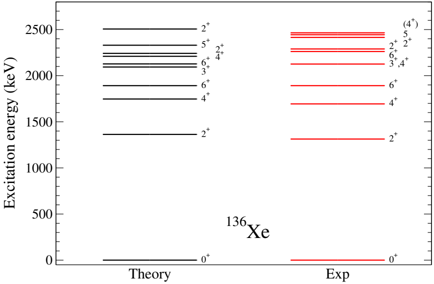
Shell model in one-major-shell spaces, phenomenological interactions

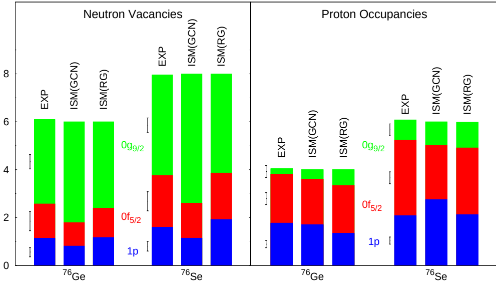
pf-shell, KB3G, GXPF1A // sd-pf space SDPFMU interaction: ^{48}Ca

$p_{3/2}, p_{1/2}, f_{5/2}, g_{9/2}$ space, GCN2850 int.: ^{76}Ge, ^{82}Se

$d_{5/2}, s_{1/2}, d_{3/2}, g_{7/2}, h_{11/2}$ space, GCN5082 int.: ^{124}Sn, ^{130}Te, ^{136}Xe

Experimental excitation spectra and occupancies well reproduced





Exp: Schiffer et al. PRL100 112501(2009), Kay et al. PRC79 021301(2009)

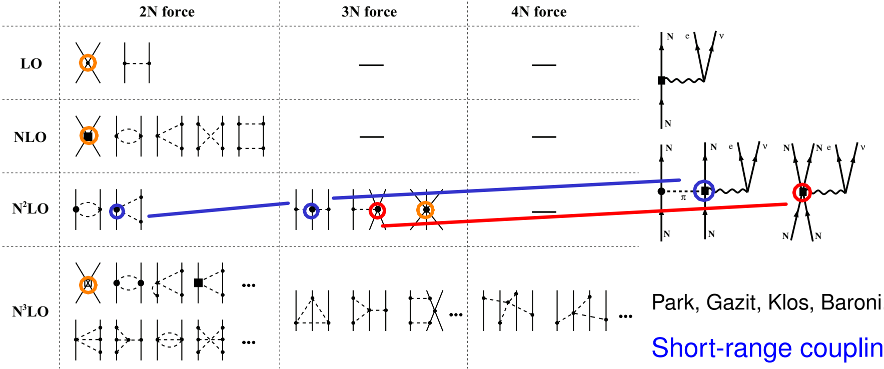
Th: JM, Caurier, Nowacki, Poves PRC80 048501 (2009)

Chiral Effective Field Theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



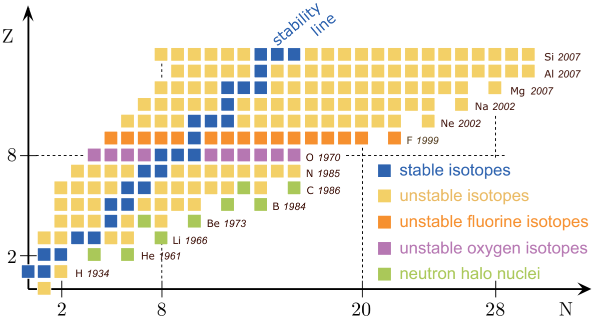
Park, Gazit, Klos, Baroni...

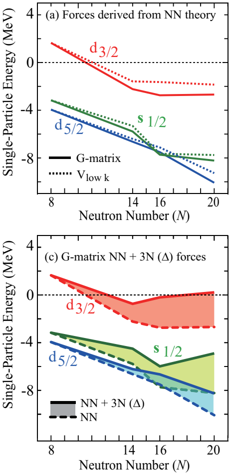
Short-range couplings fitted to experiment once

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

Oxygen dripline and 3N forces

O isotopes: ’anomaly’ in the dripline at ^{24}O, doubly magic nucleus



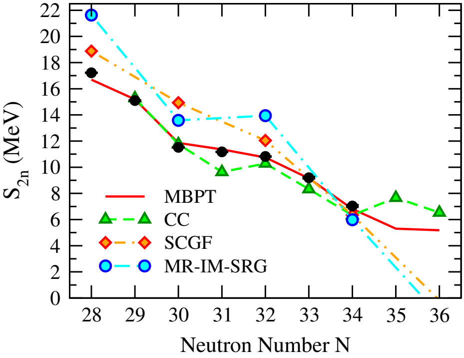


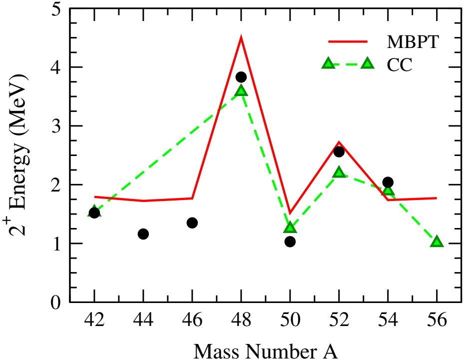
Calculations based on chiral NN+3N forces and MBPT correctly predict dripline at ^{24}O

Otsuka et al. PRL 105 032501 (2010)

Calcium isotopes with NN+3N forces

Calculations with NN+3N forces predict shell closures at ^{52}Ca, ^{54}Ca

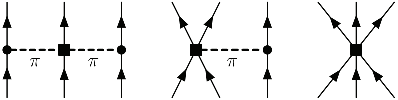




^{51,52,53,54}Ca masses [TRIUMF/ISOLDE]

^{54}Ca 2_1^+ state excitation energy [RIBF]

Hebeler et al. ARNPS 65 457 (2015)



Two-body currents in light nuclei

Two-body (meson-exchange) currents tested in light nuclei, electromagnetic and weak interactions studied:

^{3}H β decay

Gazit et al. PRL103 102502(2009)

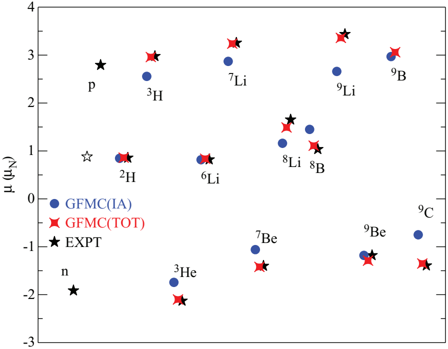
$A \leq 9$ magnetic moments
^{8}Be EM transitions

Pastore et al. PRC87 035503(2013) $\Longrightarrow$

Pastore et al. PRC90 024321(2014)

^{3}H μ capture

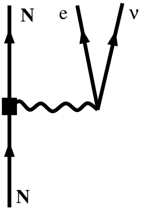
Marcucci et al. PRC83 014002(2011)



2b current contributions $\sim$ few % in light nuclei ($Q \sim \sqrt{BEm}$)
2b currents order Q^3 $\Rightarrow$ larger effect in medium-mass nuclei ($Q \sim k_F$)

Hadronic weak currents in chiral EFT

At lowest orders Q^0, Q^2 1b currents only



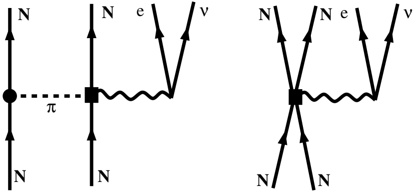
$$J_i^0(p) = g_V(p^2)\tau^-,$$

$$\boldsymbol{J}_i(p) = \left[g_A(p^2)\boldsymbol{\sigma} - g_P(p^2)\frac{(\boldsymbol{p}\cdot\boldsymbol{\sigma}_i)\boldsymbol{p}}{2m} + i\,(g_M+g_V)\,\frac{\boldsymbol{\sigma}_i\times\boldsymbol{p}}{2m}\right]\tau^-,$$

At order Q^3 chiral EFT
2b currents predicted

Reflect interactions
between nucleons in nuclei

Long-range currents dominate

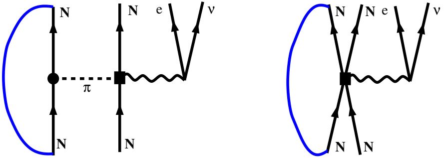


$$\mathbf{J}_{12}^3 = -\frac{g_A}{4F_\pi^2}\frac{1}{m_\pi^2+k^2}\left[2c_4\mathbf{k}\times(\boldsymbol{\sigma}_\times\times\mathbf{k})\tau_\times^3 + 4c_3\mathbf{k}\cdot\left(\boldsymbol{\sigma}_1\tau_1^3+\boldsymbol{\sigma}_2\tau_2^3\right)\mathbf{k}\right]$$

2b currents in medium-mass nuclei

Approximate in medium-mass nuclei:
normal-ordered 1b part with respect to spin/isospin symmetric Fermi gas

Sum over one nucleon, direct and the exchange terms



$\Rightarrow \mathbf{J}^{\mathrm{eff}}_{n,2b}$ normal-ordered 1b current

Corrections $\sim (n_{\mathrm{valence}}/n_{\mathrm{core}})$
in Fermi systems

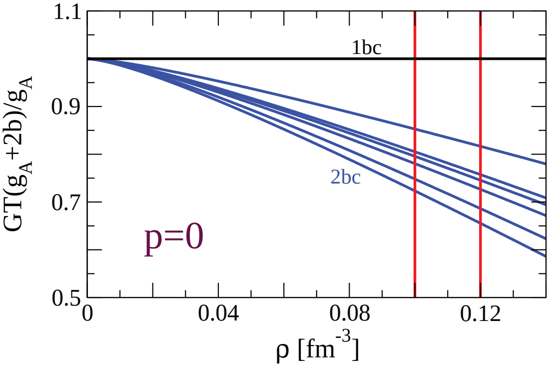
The normal-ordered two-body currents modify GT operator

$$\mathbf{J}^{\mathrm{eff}}_{n,2b} = -\frac{g_A \rho}{f_\pi^2} \tau_n^- \boldsymbol{\sigma}_n \left[I(\rho, P) \left(\frac{2c_4 - c_3}{3} \right) + \frac{2}{3} c_3 \frac{\mathbf{p}^2}{m_\pi^2 + \mathbf{p}^2} \right],$$

p independent p dependent

2b currents and GT quenching

2b currents, $p = 0$: GT, $2\nu\beta\beta$ decays $\quad \mathbf{J}^{\rm eff}_{n,2b} = -\frac{g_A \rho}{f_\pi^2} \tau_n^- \boldsymbol{\sigma}_n \left[I(\rho, P) \left(\frac{2c_4 - c_3}{3} \right) \right]$



JM, Gazit, Schwenk PRL107 062501 (2011)

General density range
$\rho = 0.10 \ldots 0.12$ fm^{-3}

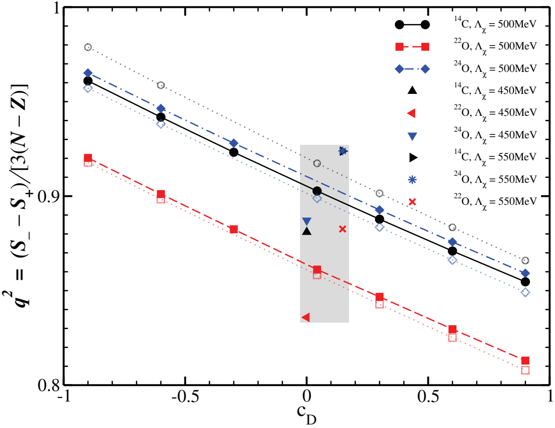
Couplings c_3, c_4
from NN potentials

Entem et al.
PRC68 041001(2003)
Epelbaum et al.
NPA747 362(2005)
Rentmeester et al.
PRC67 044001(2003)
$\delta c_3 = -\delta c_4 \approx 1$ GeV^{-1}

2b currents predict $\boldsymbol{\sigma}\tau$ quenching $q = 0.85 \ldots 0.66$

2b currents: Coupled-Cluster calculations

Coupled-cluster calculations for single-β decay (GT strengths) including chiral 1b+2b currents in light ^{14}C, ^{22}O and ^{24}O



Calculation with chiral EFT NN+3N forces 1b+2b currents

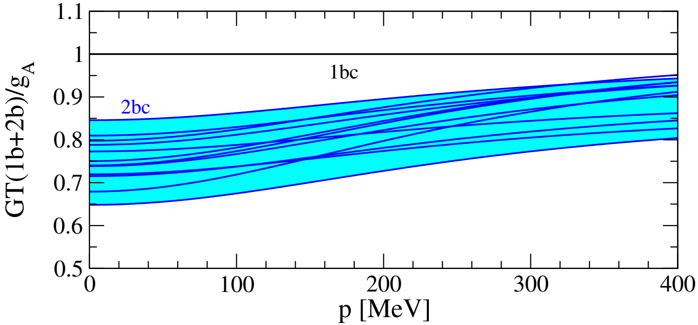
Normal-ordered 1b part with respect to Hartree-Fock state

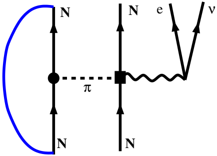
From 2b currents predict small $\sigma\tau$ quenching $q = 0.96...0.92$

Ekström et al. PRL113 262504 (2014)

2b currents: transferred-momentum dependence

2b currents depend on transferred momentum *p*: $-\frac{g_A\rho}{f_\pi^2}\tau_n^-\sigma_n\left[\frac{2}{3}c_3\frac{\mathbf{p}^2}{m_\pi^2+\mathbf{p}^2}\right]$





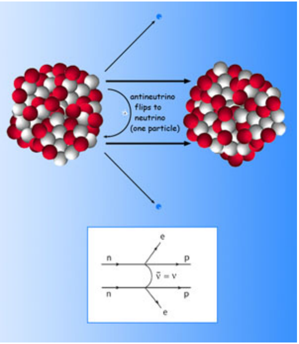
JM, Gazit, Schwenk PRL107 062501 (2011)

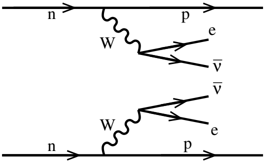
Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$ and other weak processes e.g. muon capture

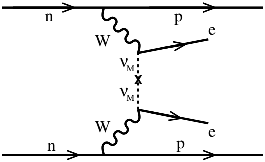
Neutrinoless double-beta decay

Neutrinoless double-beta ($0\nu\beta\beta$) decay:
Lepton-number violation, Majorana nature of neutrinos

Nuclear matrix elements combined with $0\nu\beta\beta$ decay lifetimes will determine the mass hierarchy of neutrinos

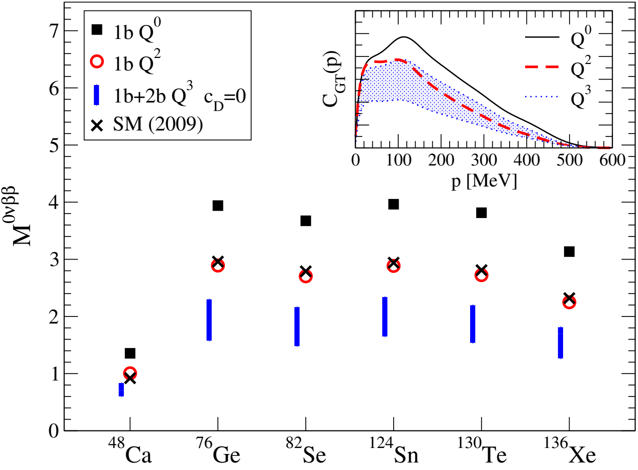






In $2\nu\beta\beta$ decay, the momentum transfer limited by $Q_{\beta\beta}$, while for $0\nu\beta\beta$ decay larger momentum transfers are permitted

$0\nu\beta\beta$ decay matrix elements with 1b+2b currents



JM, Gazit, Schwenk PRL107 062501 (2011)

Order Q^0+Q^2 similar to phenomenological currents

JM, Poves, Caurier, Nowacki NPA818 139 (2009)

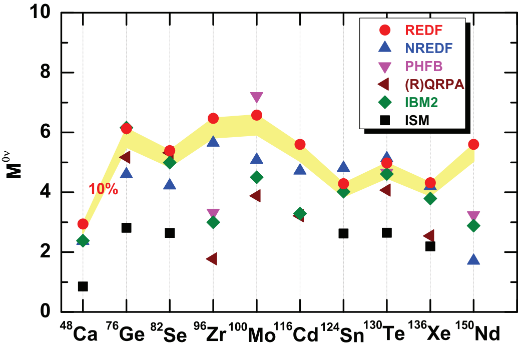
Order Q^3
2b currents reduce NMEs $\sim 15\% - 40\%$

Smaller than -50% $(q^2 = 0.7^2)$ due to momentum-transfer $p > 0$

2b currents need to be included in all approaches calculating $0\nu\beta\beta$ decay

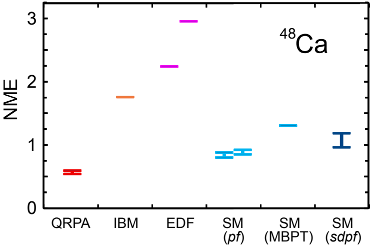
Neutrinoless $\beta\beta$ decay matrix elements

Large difference in matrix element calculations, same transition operator



Yao et al. PRC91 024316 (2015)

EDF, IBM, QRPA
large matrix elements:
How well include nuclear
structure correlations?
Pairing, deformation,
isoscalar pairing...



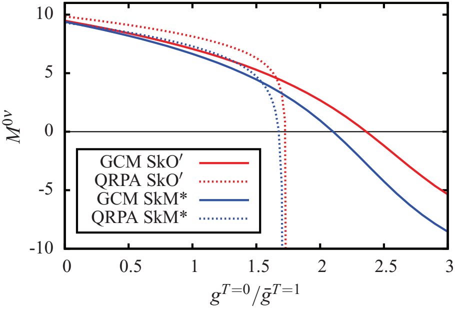
Iwata et al. (2015)

Shell model small matrix elements:
What is the effect of the valence space?

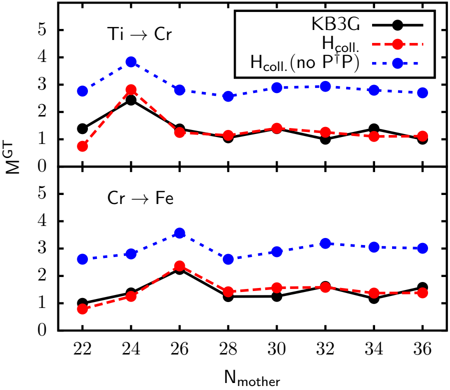
Isoscalar pairing and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay very sensitive to isoscalar (proton-neutron) pairing

Matrix elements too large if proton-neutron correlations are neglected



Hinohara, Engel PRC90 031301 (2014)

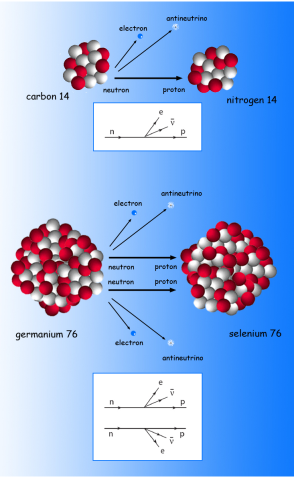


JM et al. arXiv:1510.06824

Related to approximate *SU*(4) symmetry of the $0\nu\beta\beta$ decay operator

Summary

Why nuclear structure calculations need to quench the $\boldsymbol{\sigma}\tau$ operator to agree with experiment remains an open puzzle



Corrections to 1b electromagnetic and weak operators shown to be needed in ab initio calculations of light nuclei

Chiral EFT predicts 2b corrections for GT transitions: approximately calculated in medium-mass nuclei

Long-range 2b currents contribute to GT quenching but actual size of this effect remains to be settled

At larger momentum transfers $p \sim m_\pi$ the quenching due to 2b currents is reduced relevant for neutrinoless double-beta decay

Collaborators

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