New insights on double-beta decay matrix elements

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Neutrino Nuclear Responses for Double Beta Decays
and Astro-Neutrino Interactions (NNR16)
RCNP, Osaka University, 30th September 2016

日本学術振興会 Japan Society for the Promotion of Science

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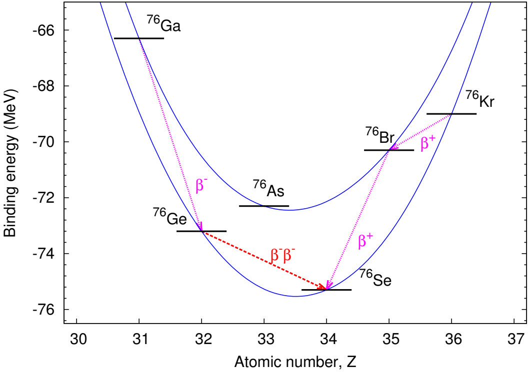
Double-beta decay

Double-beta decay is a second-order process,
only to be observed when single-β decay is forbidden or suppressed



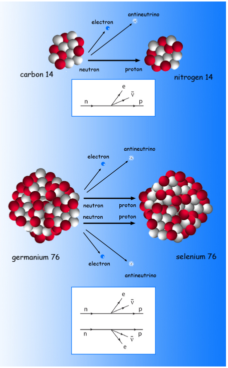
Transition	Experiment
^{48}Ca $\rightarrow$ ^{48}Ti	CANDLES
^{76}Ge $\rightarrow$ ^{76}Se	GERDA, MAJORANA
^{82}Se $\rightarrow$ ^{82}Kr	SuperNEMO
^{96}Zr $\rightarrow$ ^{96}Mo	
^{100}Mo $\rightarrow$ ^{100}Ru	AMoRE
^{110}Pd $\rightarrow$ ^{110}Cd	
^{116}Cd $\rightarrow$ ^{116}Sn	COBRA
^{124}Sn $\rightarrow$ ^{124}Te	
^{130}Te $\rightarrow$ ^{130}Xe	CUORE, SNO+
^{136}Xe $\rightarrow$ ^{136}Ba	EXO, KamLAND-Zen, NEXT
^{150}Nd $\rightarrow$ ^{150}Sm	

Present half-life limits in ^{76}Ge, ^{136}Xe set to $T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y, 10^{26} y!

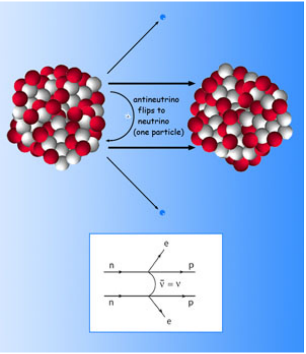
Lepton-number conservation

Lepton number is conserved
in all physical processes
observed to date

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



β decay, $\beta\beta$ decay...

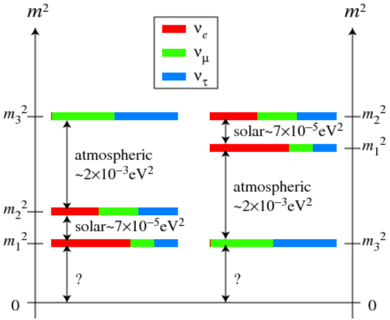


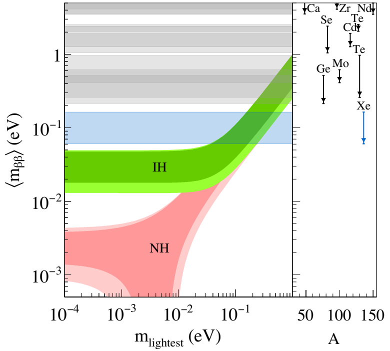
Neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay

Neutrino mass hierarchy

The decay lifetime is $\left(T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2,$

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





Matrix elements needed to make sure next generation ton-scale experiments fully explore "inverted hierarchy"

KamLAND-Zen: PRL117 082503(2016)

$0\nu\beta\beta$ decay mechanisms

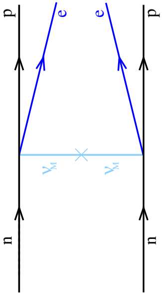
$0\nu\beta\beta$ process needs massive Majorana neutrinos ($\nu = \bar{\nu}$), but several mechanisms mediating the decay are possible

$$\left(T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)\right)^{-1} = \sum_i G_i \left|M_i^{0\nu\beta\beta}\right|^2 (\eta_i)^2$$

G_i is the phase space factor: $Q_{\beta\beta}$, leptons...

$M_i^{0\nu\beta\beta}$ is the nuclear matrix element

η_i describes new physics

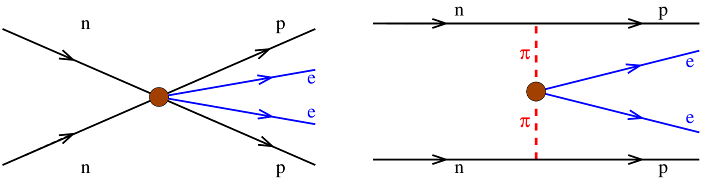


Exchange of
Standard Model neutrinos ($\eta = m_{\beta\beta}$),
sterile neutrinos ($\eta \sim m_\nu$),
left-right symmetric models ($\eta \sim W_R$ mass, $W_R - W_L$ mixing),
exchange of supersymmetric particles ($\eta \sim$ LNV couplings)

$0\nu\beta\beta$ decay constrains new physics models

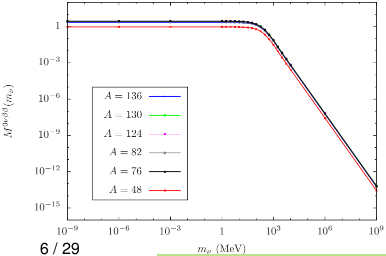
$0\nu\beta\beta$ decay and new physics

Calculate nuclear matrix elements for new physics mechanisms



In heavy-particle exchange, the exchange of pions dominate

Prezeau et al. PRD68 034016(2003)



Retamosa et al. PRC51 371 (1995)

Hirsch et al. PRL75 17 (1995)

Blennow et al. JHEP07 096 (2010)

Meroni et al. JHEP02 025 (2013)

Hyvärinen et al. PRC91 024613 (2015)

Barea et al. PRC92 092001 (2015)

Horoi et al. PRD93 103014 (2016)

...

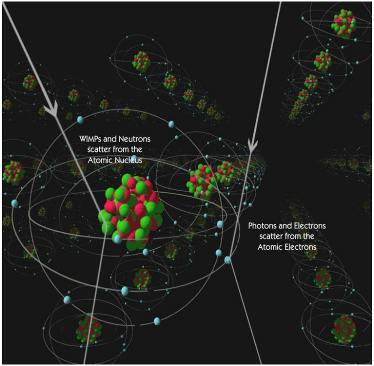
Nuclear matrix elements

The Nuclear Matrix Element of the process has to be evaluated

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

Nuclear structure calculation of the initial and final states:
Ab initio, phenomenological...

Description of the lepton-nucleus interaction:
Evaluation (non-perturbative) of the hadronic currents inside nucleus: phenomenological, effective theory



CDMS Collaboration

Many-body approaches for $0\nu\beta\beta$ decay

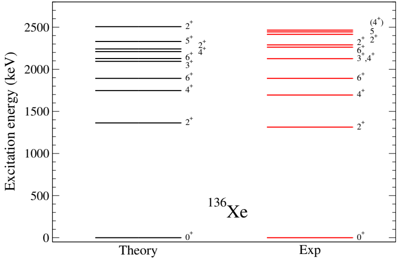
Several many-body methods used to obtain $0\nu\beta\beta$ decay matrix elements

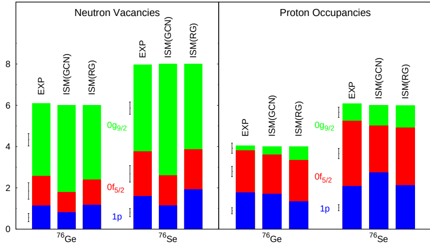
- Shell model (phenomenological)
  Retamosa, Caurier, Nowacki, Poves, JM, Horoi, Brown, Otsuka, Shimizu...
- Energy density functional
  Rodríguez, Martínez-Pinedo, Yao...
- Quasiparticle random phase approximation (QRPA)
  Vogel, Engel, Faessler, Šimkovic, Rodin, Fang, Suhonen...
- Interacting boson model
  Barea, Kotila, Iachello...

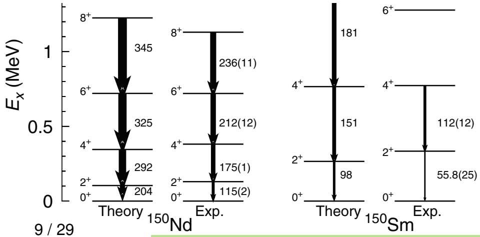
Strong interest in nuclear theory community:
Ab initio shell model, Coupled Cluster, in-medium SRG...
More controlled calculations with estimated uncertainties

Test of nuclear structure

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







Shell model:
JM, Caurier, Nowacki, Poves
PRC80 048501 (2009)

Energy Density Functional:
Rodríguez, Martínez-Pinedo
PRL105 252503 (2010)

Neutrinoless $\beta\beta$ decay operator

The matrix element is $$M^{0\nu\beta\beta} = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\, \Omega^X \, |0_i^+\rangle$$

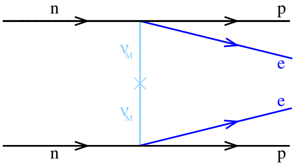
- $\tau_n^- \tau_m^-$ transform two neutrons into two protons
- Ω^X is the spin structure:
  Fermi ($\mathbb{1}$), Gamow-Teller ($\sigma_n \sigma_m$), Tensor $\left[Y^2(\hat{r})\,[\sigma_n\sigma_m]^2\right]^0$
- $H(r)$ is the neutrino potential, depends on m_ν

$$H^X(r) = \frac{2}{\pi}\frac{R}{g_A^2(0)}\int_0^\infty f^X(pr)\frac{h^X(p^2)}{\left(\sqrt{p^2+m_\nu^2}\right)\left(\sqrt{p^2+m_\nu^2}+\langle E^m\rangle - \frac{1}{2}(E_i - E_f)\right)}p^2\,dp \sim \frac{R}{r}$$

Closure approximation typically used
tested to be valid to $\sim 10\%$

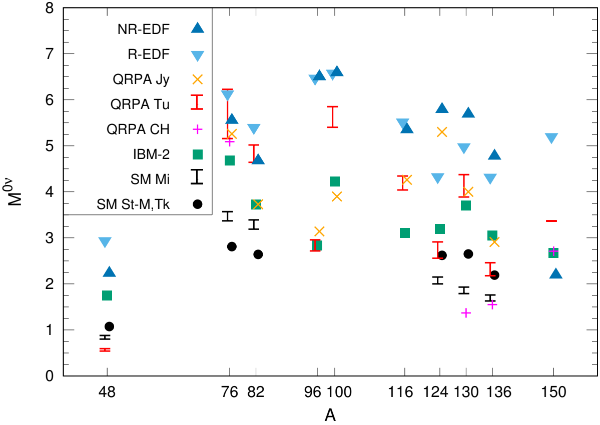
Muto NPA577 415C(1994)

Sen'kov et al. PRC90 051301(2014)



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

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

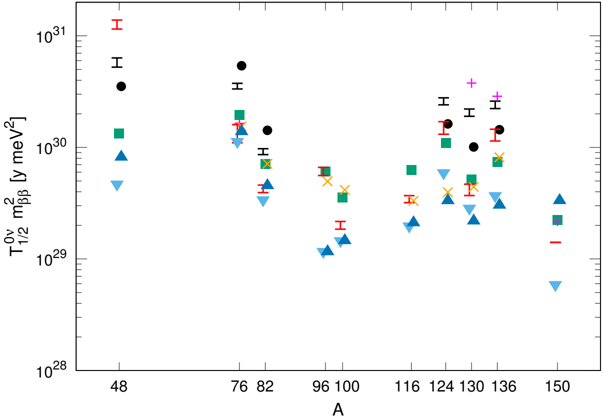


EDF, IBM, QRPA large matrix elements: missing nuclear correlations?

Shell model small matrix elements: small configuration space?

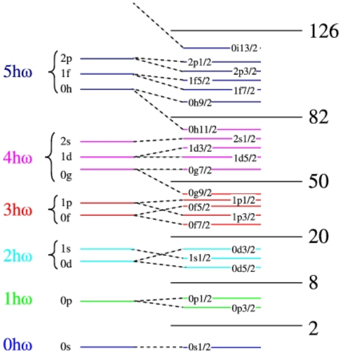
Favored material for experiment?

From nuclear matrix elements, no preferred candidate for experiment



Material to be used, based on experimental/technological advantages

Shell model



Solve the many-body problem "exactly" around the Fermi level

- Excluded orbitals:
  orbitals always empty
- Valence space:
  configuration space where to solve the many-body problem
- Inner core:
  orbitals always filled

Diagonalize valence space, other effects in H_{eff}:

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

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

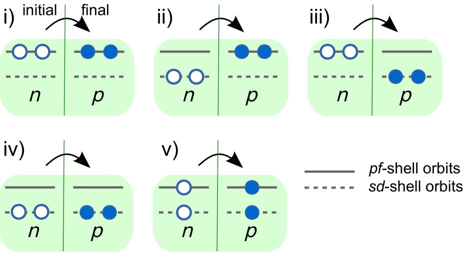
Exact diagonalization: 10^{11} dimension Caurier et al. RMP77 427 (2005)

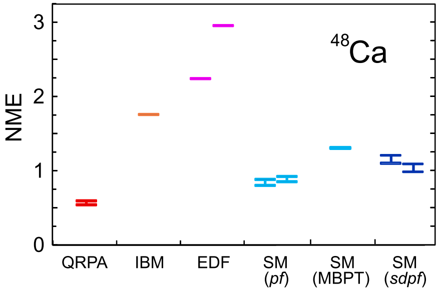
Monte Carlo shell model: 10^{23} dimension Togashi et al. arXiv:1606.09056

Shell model configuration space

For ^{48}Ca enlarge configuration space from *pf* to *sdpf* (4 to 7 orbitals) increases matrix elements but only moderately $\sim$ 30%

Iwata et al. PRL116 112502 (2016)





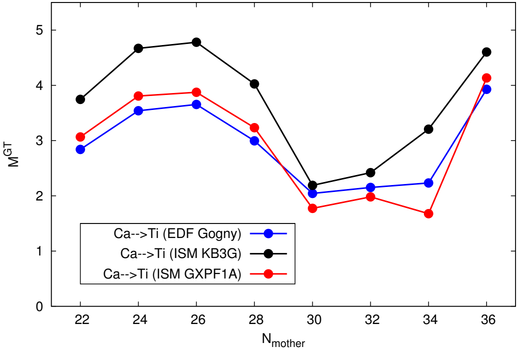
The contributions dominated by pairing (2p-2h) excitations enhance the $\beta\beta$ matrix element, but the contributions dominated by 1p-1h excitations suppress the $\beta\beta$ matrix element

Otsuka san's talk

$0\nu\beta\beta$ 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)

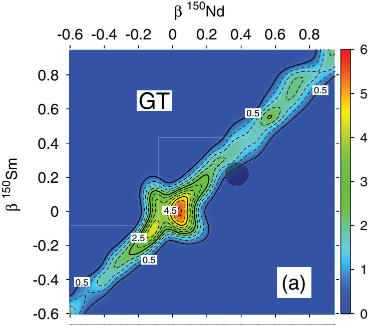
NME follows generalized seniority model:

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

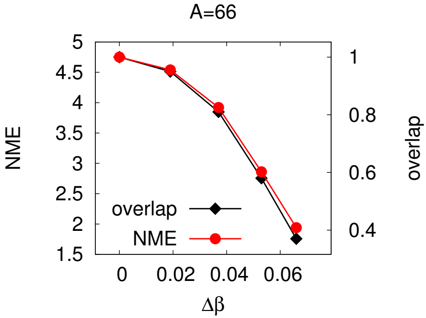
Deformation and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay is disfavoured by quadrupole correlations

$0\nu\beta\beta$ decay very suppressed when nuclei have different structure



Rodríguez, Martínez-Pinedo
PRL105 252503 (2010)



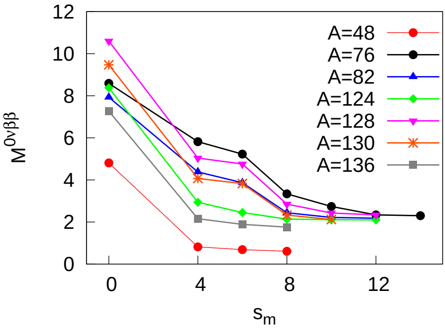
JM, Caurier, Nowacki, Poves
JPCS267 012058 (2011)

Suppression also observed with QRPA Fang et al. PRC83 034320 (2011)

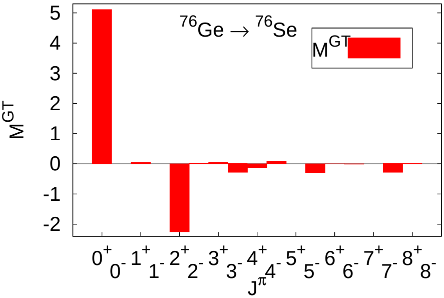
Pairing correlations and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay is favoured by pairing correlations

Ideal case: superfluid nuclei
reduced with high-seniorities



Dominant contribution
decaying neutron $J = 0^+$ pairs

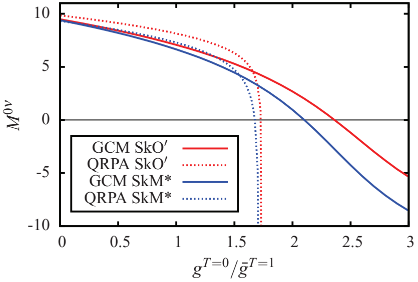


Caurier et al. PRL100 052503 (2008)

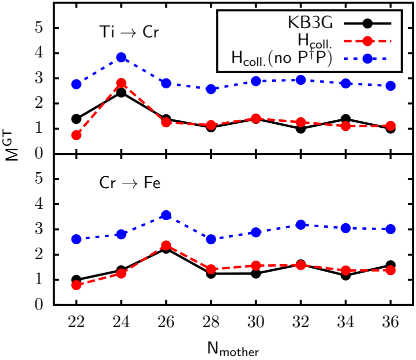
Proton-neutron pairing and $0\nu\beta\beta$ decay

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

Matrix elements too large if proton-neutron correlations are neglected



Hinohara, Engel PRC90 031301 (2014)

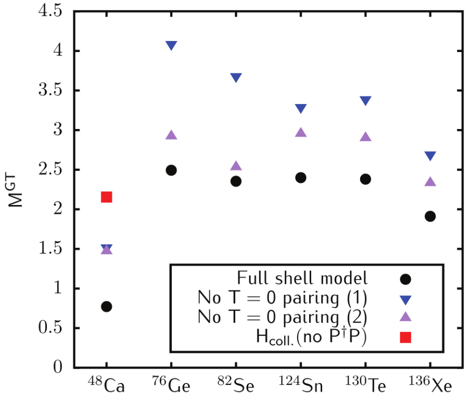


JM et al. PRC93 014305 (2016)

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

Isoscalar pairing in $\beta\beta$ decay emitters

Estimate isoscalar pairing in ^{76}Ge, ^{82}Se, ^{124}Sn, ^{130}Te, ^{136}Xe decays



JM et al. PRC93 014305 (2016)

(1) Set to zero all interaction matrix elements receiving contributions from collective isoscalar pairing interaction

(2) Subtract isoscalar pairing assuming pf-shell strength

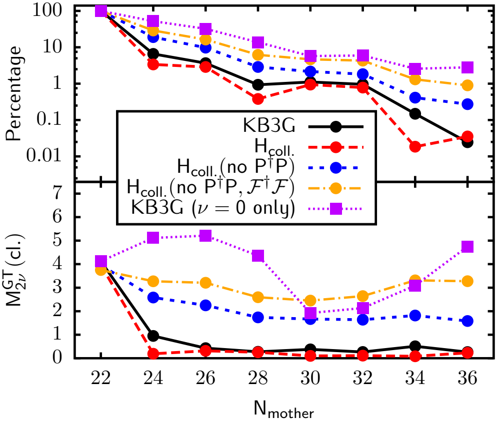
Estimations suggest NMEs could be overestimated without isoscalar pairing around 10% – 50% effect

SU(4) symmetry: small matrix elements

Exact SU(4) symmetry $\Rightarrow M^{0\nu\beta\beta} = 0$
(mother and daughter nuclei in different SU(4) irreps)

SU(4) broken in nuclei
(spin-orbit force...)
but relatively small fraction
of mother and daughter nuclei
in same SU(4) irrep

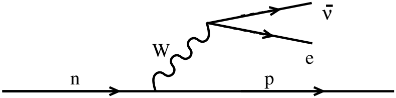
When neutrino potential is
omitted, $0\nu\beta\beta$ operator exactly
symmetric under SU(4):
Matrix elements almost vanish



Missing correlations breaking SU(4) symmetry, strongly impact $\beta\beta$ decay

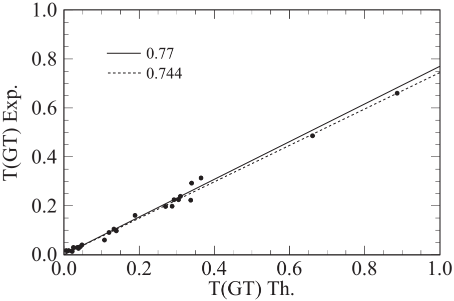
Gamow-Teller transitions: "quenching"

Single-β decays well described by nuclear structure (shell model)



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

$$g_A^{\text{eff}} = q g_A, \quad q \sim 0.7 - 0.8.$$



Theory needs to “quench“ $\sigma\tau$ operator to predict Gamow-Teller lifetimes

This puzzle has been the target of many theoretical efforts:

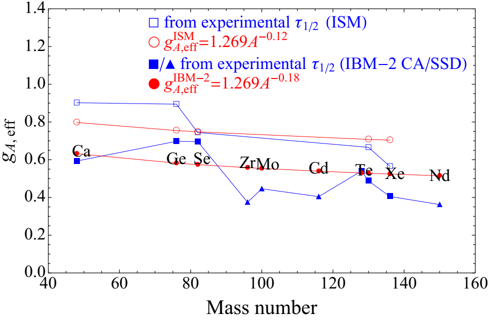
Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...

Anything missing in the many-body approach? **Ejiri san’s talk...**

Anything missing in the transition operator? **This talk**

Gamow-Teller transitions: "quenching"

The spin-isospin quenching is also present when studying $2\nu\beta\beta$ decays



In heavier nuclei quenching is larger possibly because of missing spin-orbit partners

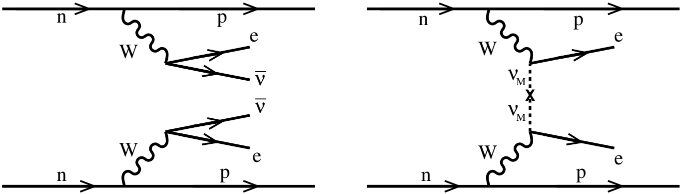
Caurier et al. PLB711 62(2012)

Barea et al. PRC91 034304(2015)

If $0\nu\beta\beta$ decay matrix elements are overpredicted in a similar amount experiments will not be able to probe the inverted hierarchy region

"Quenching" in $0\nu\beta\beta$ vs $2\nu\beta\beta$ decays

From the theoretical point of view, $0\nu\beta\beta$ and $2\nu\beta\beta$ decays are different



- In $2\nu\beta\beta$ decay, the momentum transfer to leptons is limited by $Q_{\beta\beta}$, while for $0\nu\beta\beta$ decay larger momentum transfers are permitted
- In $2\nu\beta\beta$ decay only 1^+ multipoles contribute, but all multipoles relevant in $0\nu\beta\beta$ decay (neutrino potential)

Does "quenching" depend on multipolarity, or momentum transfer?

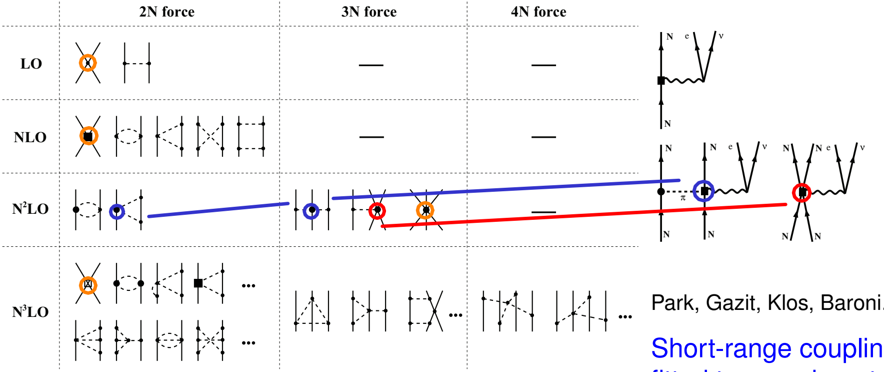
Ejiri et al. PLB729 27 (2014)...

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...

2b currents in light nuclei

2b currents (meson-exchange currents) tested in light nuclei:

^{3}H β decay

Gazit et al. PRL103 102502(2009)

$A \leq 9$ magnetic moments

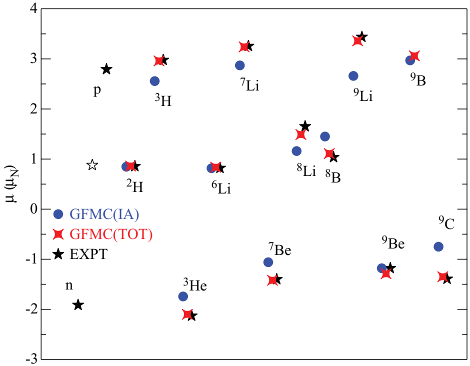
^{8}Be EM transitions

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

Pastore et al. PRC90 024321(2014)

^{3}H μ capture

Marcucci et al. PRC83 014002(2011)

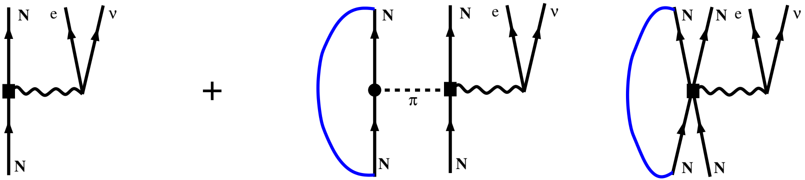


In light nuclei, 2b current effect relatively small

How is the scaling to medium-mass and heavy nuclei?

Hadronic 1b + 2b weak currents

Include 1b and 2b currents (operators) from chiral EFT
reflect strong interactions between nucleons in nuclei



The normal-ordered two-body currents modify GT operator

$$\mathbf{J}^{\mathrm{eff}}_{n,2b} = -\frac{g_A \rho}{f_\pi^2} \tau_n^- \sigma_n \left[I(\rho, P) \left(\frac{1}{3} (2c_4 - c_3) \right) + \frac{2}{3} c_3 \frac{\mathbf{p}^2}{m_\pi^2 + \mathbf{p}^2} \right],$$

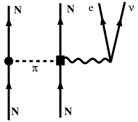
p independent p dependent

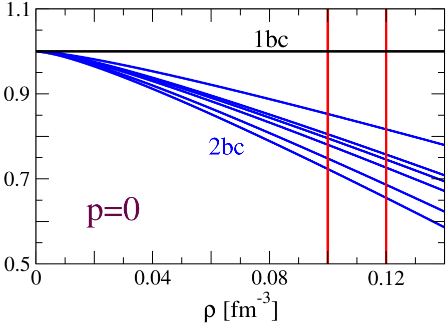
2b currents in medium-mass nuclei

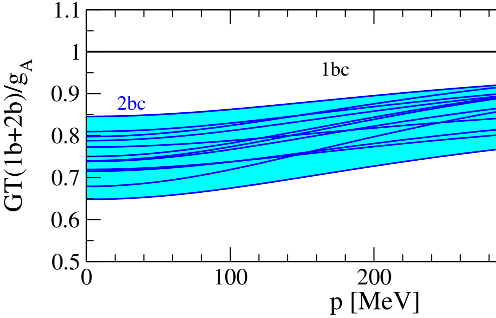
Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

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



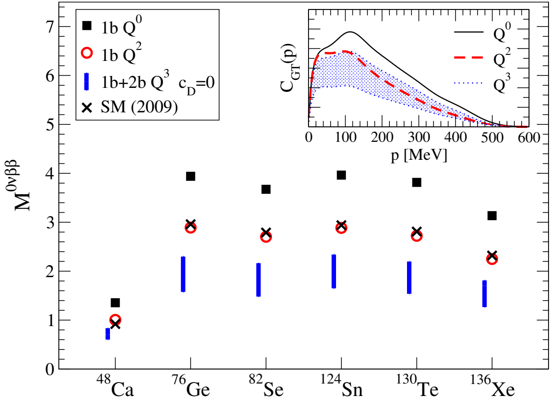




2b currents predict g_A quenching $q = 0.85 \ldots 0.66$

Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$

Nuclear matrix elements with 1b+2b currents



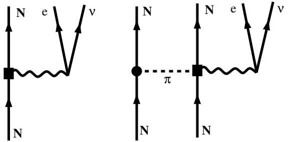
JM, Gazit, Schwenk PRL107 062501 (2011)

JM arXiv:1605.05059, updated 2b currents

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

JM, Poves, Caurier, Nowacki

NPA818 139 (2009)



Order Q^3 2b currents reduce NMEs $\sim 20\% - 50\%$

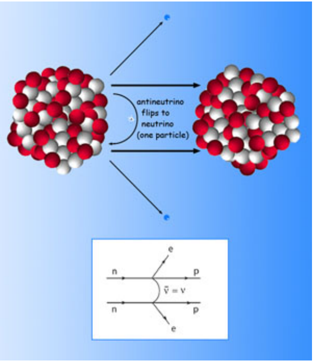
Smaller quenching $q = 0.96...0.92$ Ekström et al. PRL113 262504 (2014)

Coupled-Cluster study of ^{14}C, ^{22,24}O, Hartree-Fock normal-ordering

Summary

Neutrinoless double-beta decay nuclear matrix elements
key to fully exploit next generation experiments testing inverted hierarchy

- Matrix element differences
  between present calculations, factor 2 – 3
- New ^{48}Ca shell model result 30% increase,
  shell model Monte Carlo underway
- Include isoscalar pairing correlations
  in EDF-type and IBM approaches
- Understand g_A quenching?
  2b currents reduce matrix elements,
  further reduction due to many-body methods?
- Ab initio calculations on the way,
  estimation of theoretical uncertainties



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