Status and future of neutrinoless $\beta\beta$ decay nuclear matrix elements

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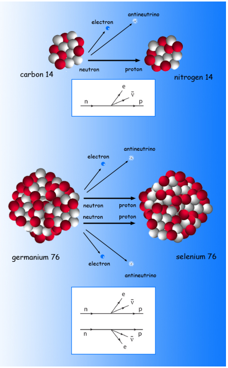
日本学術振興会
Japan Society for the Promotion of Science

科研費
KAKENHI

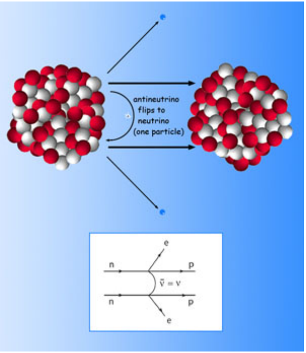
Lepton-number conservation

Lepton number is conserved
in all physical processes
observed to date

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



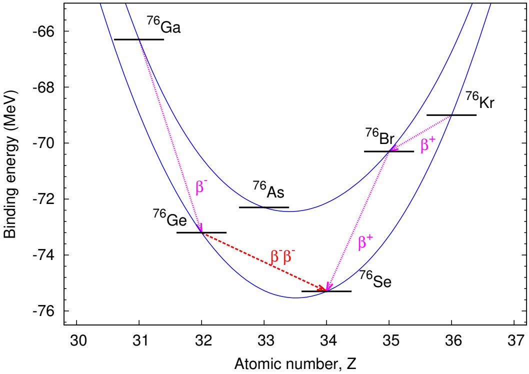
β decay, $\beta\beta$ decay...



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

Double-beta decay

Double-beta decay is a second-order process,
only to be observed when single-β decay is energetically forbidden
or hindered by large spin difference between initial and final states



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

$0\nu\beta\beta$ decay mechanisms

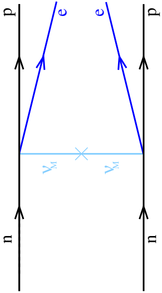
$0\nu\beta\beta$ process needs massive Majorana neutrinos ($\nu = \bar{\nu}$),
but several mechanisms mediating the decay are possible

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

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

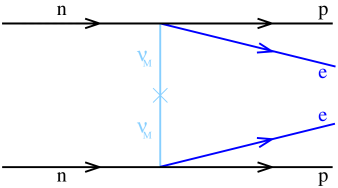


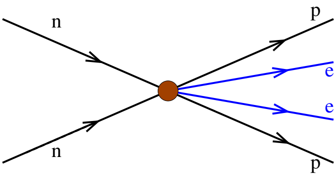
Exchange of
Standard Model neutrinos ($\eta = m_{\beta\beta}$),
sterile neutrinos ($\eta \sim m_\nu$),
left-right symmetric models ($\eta \sim W_R$ mass, $W_R - W_L$ mixing),
exchange of supersymmetric particles ($\eta \sim$ LNV couplings)

Possible to constrain new physics beyond neutrino masses

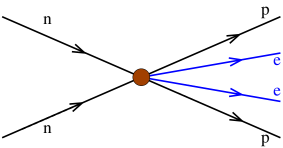
Standard Model and new physics

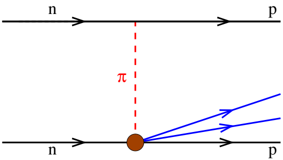
Exchange of Standard Model neutrinos: standard scenario
Exchange of heavy particles test new physics

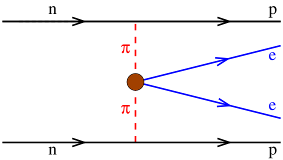




For the exchange of heavy particles pion physics plays key role,
long-range terms dominant in EFT expansion Prezeau et al. PRD68 034016(2003)
short-range diagrams additionally suppressed: nucleons $\sim$ 1 fm away



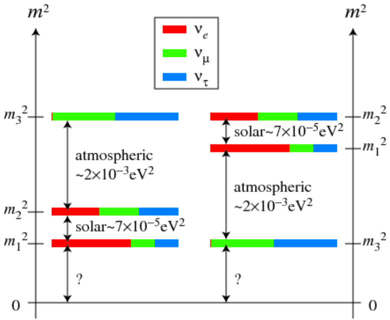


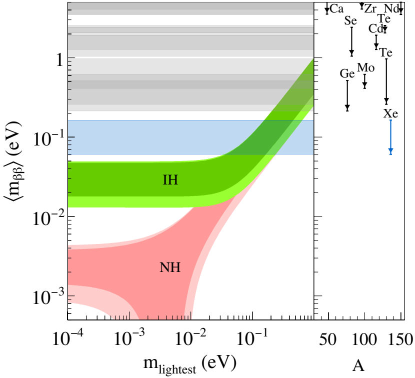


Input from Lattice QCD **A. Walker-Loud** plenary talk

Neutrino mass hierarchy

The decay lifetime is
$$\left(T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2,$$
sensitive to absolute neutrino masses, $m_{\beta\beta} = \left|\sum U_{ek}^2 m_k\right|$, and hierarchy





Matrix elements needed to make sure

KamLAND-Zen collaboration

next generation one-tonne experiments fully cover inverted hierarchy region

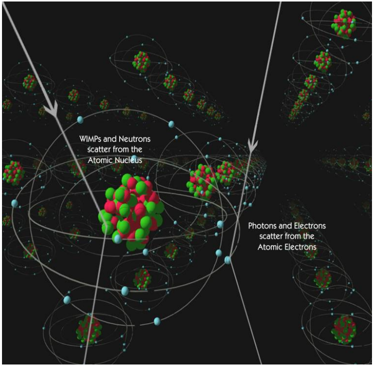
Nuclear matrix elements

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



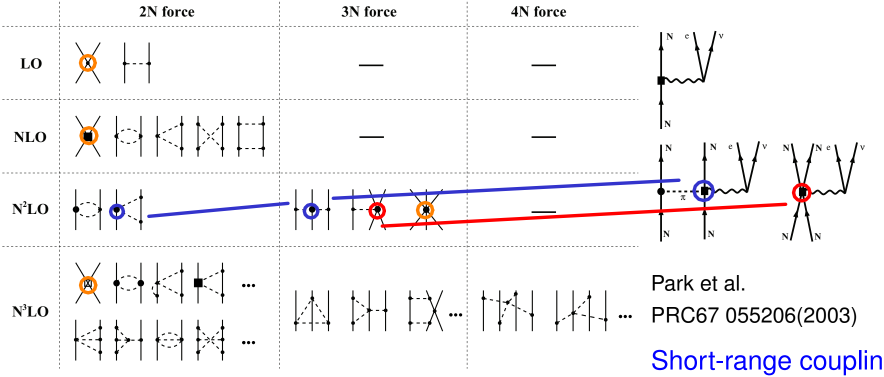
CDMS Collaboration

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 currents



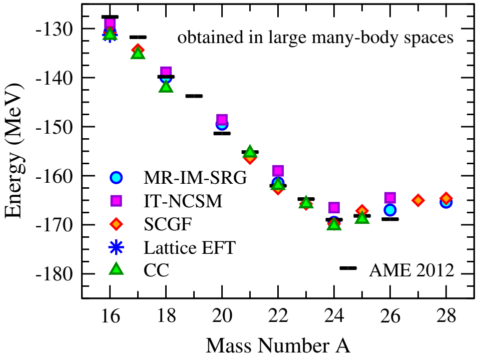
Weinberg, van Kolck, Kaplan, Savage, Meißner, Epelbaum, Weise...

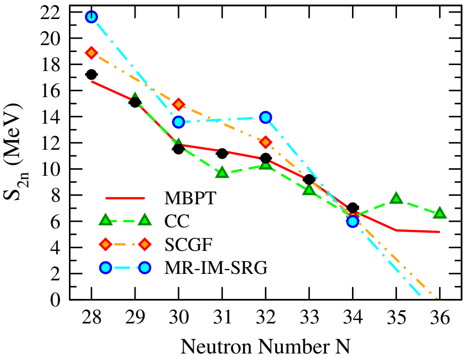
Park et al.
PRC67 055206(2003)

Short-range couplings fitted to experiment once

Nuclear structure wich chiral EFT forces

Great sucess prediction of oxygen dripline and calcium separation energies





Hergert et al. PRL110 242501 (2013)

Cipollone et al. PRL111 062501 (2013)

Jansen et al. PRL113 142502 (2014)

Gallant et al. PRL 109 032506 (2012)

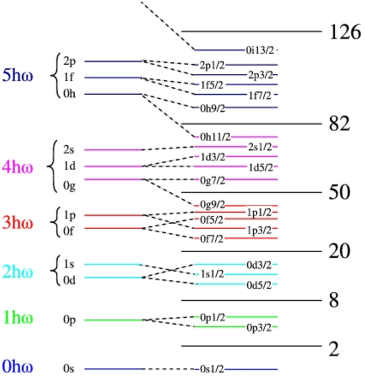
Wienholtz et al. Nature 498 346 (2013)

Hagen et al. PRL 109 032502 (2012)

Somà et al. PRC 89 061301 (2014)

Hergert et al. PRC 90 041302 (2014)

Nuclear shell model (Configuration Interaction)



Nuclear shell model configuration space only keep essential degrees of freedom

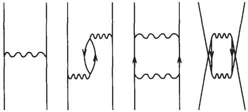
- Outer orbits: always empty
- Valence space: where many-body problem is solved
- Inner core: always filled

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

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

Many-body perturbation theory to generate H_{eff}
very recently non-perturbative methods:
VS-IMSRG, CCEI also available

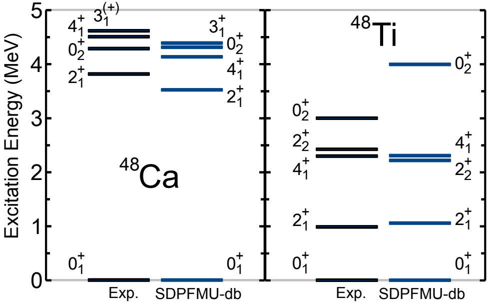
Two-Body Matrix Elements



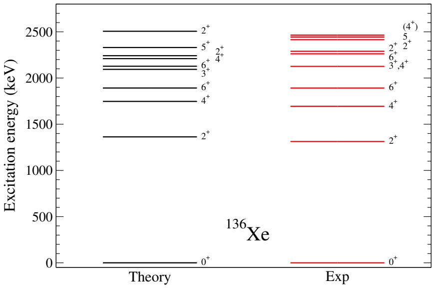
Shell model codes diagonalize up to
Exact: $\sim 10^{10}$ Slater det. Caurier *et al.* RMP 77 (2005)
Approximate: $\sim 10^{20}$ Slater det. Togashi *et al.* PRL 117 (2016)

Excitation spectra

For $0\nu\beta\beta$ decay candidates very good agreement with experiment



Iwata et al. PRL116 112502 (2016)



Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)

Other quantities such as electromagnetic transitions, occupation numbers... also in good agreement to experiment

Phenomenological calculations, systematic uncertainties difficult to quantify

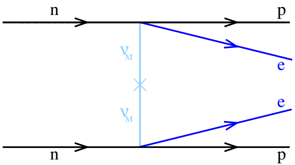
Neutrinoless $\beta\beta$ decay operator

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 $\left[Y^2(\hat{r}) \left[\sigma_n \sigma_m\right]^2 \right]^0$
- $H(r)$ is the neutrino potential, depends on m_ν

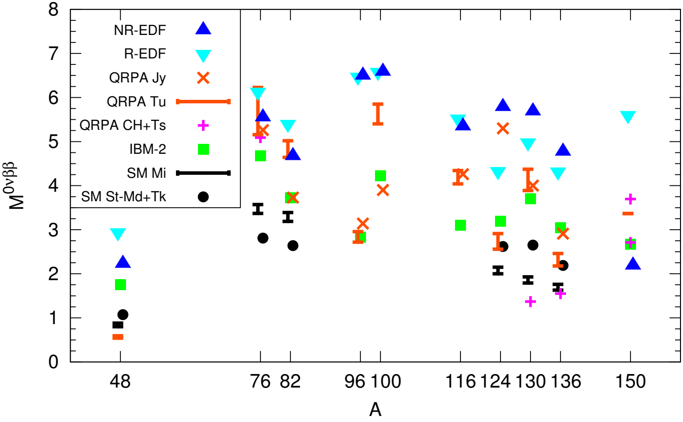
$$H^X(r) = \frac{2}{\pi} \frac{R}{g_A^2(0)} \int_0^\infty f^X(pr) \frac{h^X(p^2)}{\left(\sqrt{p^2+m_\nu^2}\right)\left(\sqrt{p^2+m_\nu^2} + \langle E^m \rangle - \frac{1}{2}(E_i - E_f)\right)} p^2 \, dp \sim \frac{R}{r}$$

$2\nu\beta\beta$ decay: momentum transfer limited by $Q_{\beta\beta}$
$0\nu\beta\beta$ decay: larger momentum transfers,
$p \sim 100-200$ MeV, set by typical distance between the two decaying nucleons



Neutrinoless $\beta\beta$ decay matrix elements

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



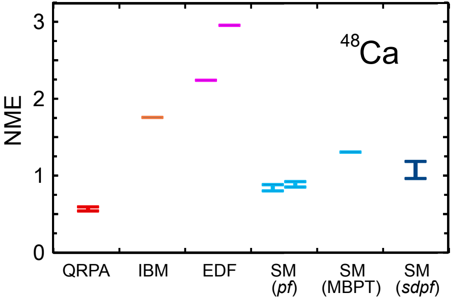
EDF, IBM, QRPA large matrix elements: missing nuclear correlations?

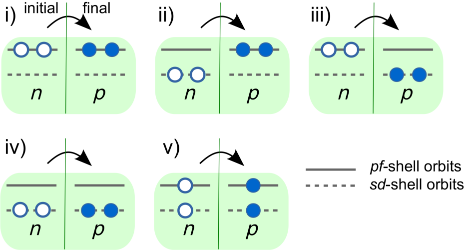
Shell model small matrix elements: Small configuration space?

Shell model configuration space

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

Iwata et al. PRL116 112502 (2016)





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

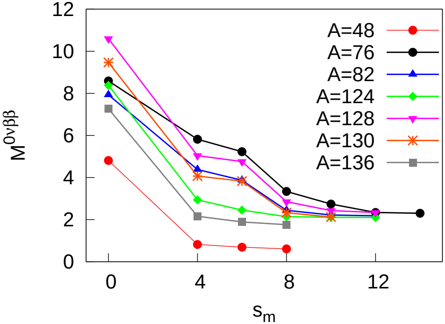
but the contributions dominated by 1p-1h excitations suppress the $\beta\beta$ matrix element

Shell model Monte Carlo calculations for heavier nuclei under way

Correlations and $0\nu\beta\beta$ decay

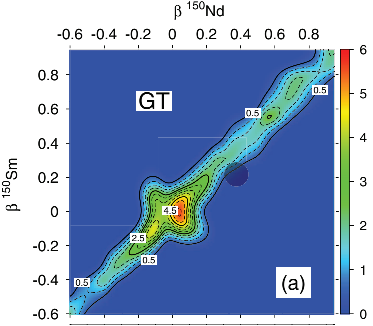
$0\nu\beta\beta$ decay sensitive to pairing, quadrupole correlations

Maximum between superfluid nuclei, reduced with broken like-particle pairs or with proton-neutron pairs



Caurier et al. PRL100 052503 (2008)

Reduced if different deformation in mother and daughter nuclei



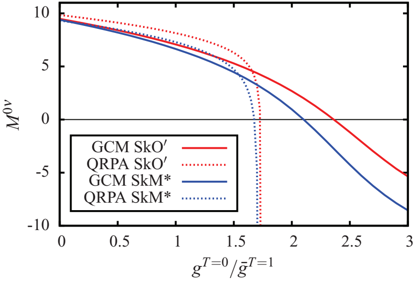
Rodríguez, Martínez-Pinedo
PRL105 252503 (2010)

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

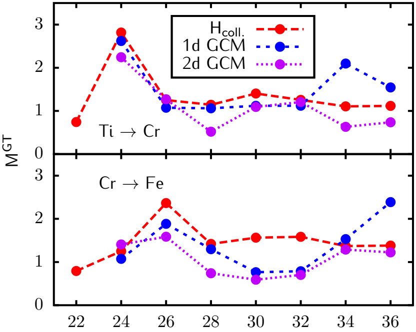
$0\nu\beta\beta$ decay very sensitive to proton-neutron (isoscalar) pairing

Matrix elements too large if proton-neutron correlations neglected

Shell model and GCM agree if proton-neutron correlations included



Hinohara, Engel PRC90 031301 (2014)



JM et al. PRC93 014305 (2016)

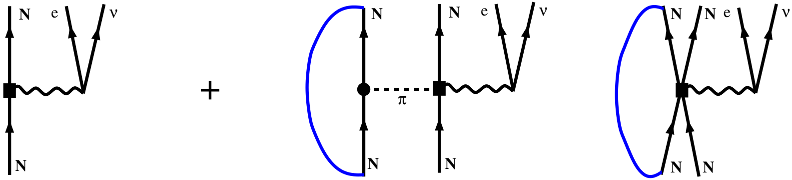
Related to approximate $SU(4)$ symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator

Weak interactions: hadronic 1b+2b currents

Single-β and $\beta\beta$ decay: $H_W = \frac{G_F}{\sqrt{2}} \left(j_{L\mu} J_L^{\mu\dagger} \right) + H.c.$

In nuclei (non-relativistic): $\langle \mathcal{N}_F | \sum_i g_V \, \tau_i^- + g_A \, \boldsymbol{\sigma}_i \tau_i^- \, | \mathcal{N}_I \rangle$
corresponding to Fermi and Gamow-Teller transitions

Include $J_L^{\mu\dagger}$ 1b and 2b currents (operators) from chiral EFT
reflect strong interactions between nucleons in nuclei



Normal-ordered long-range two-body currents modify Gamow-Teller operator

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

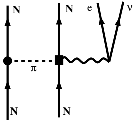
p independent *p* dependent

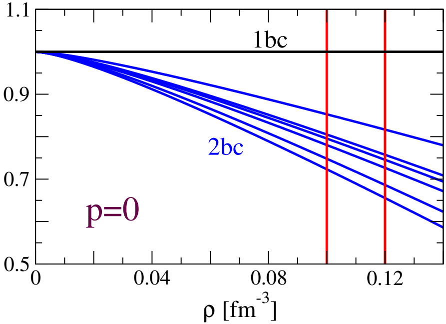
2b currents in medium-mass nuclei

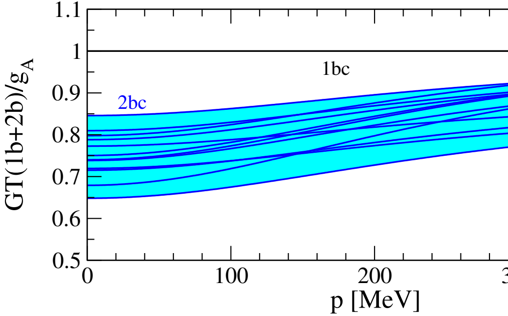
Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

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



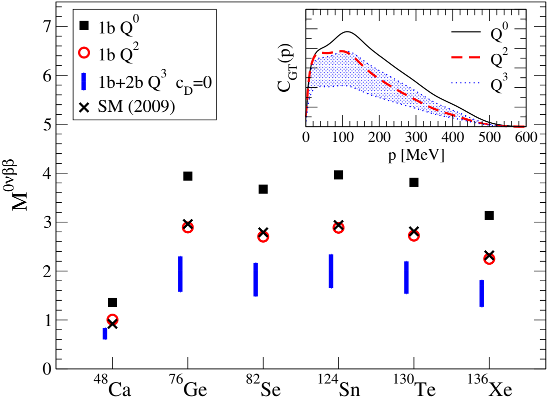




2b currents predict g_A quenching $q = 0.85...0.66$

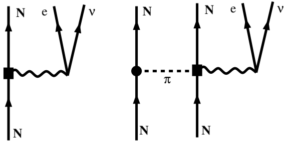
Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$

Nuclear matrix elements with 1b+2b currents



JM, Gazit, Schwenk PRL107 062501 (2011)

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%

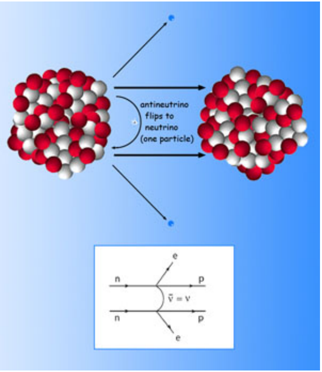
Smaller quenching $q = 0.96 \ldots 0.92$ Ekström et al. PRL113 262504 (2014)
Coupled-Cluster study of ^{14}C, ^{22,24}O, Hartree-Fock normal-ordering

Systematic calculations in light nuclei under way

Summary

Neutrinoless double-beta decay key process to understand
Majorana neutrino character and neutrino absolute mass and hierarchy

- Matrix element differences
  between present calculations, factor $2-3$
- New ^{48}Ca shell model result $\sim 30\%$ increase
  Shell model Monte Carlo underway
- Include isoscalar pairing correlations
  in EDF-type approaches
- Phenomenological matrix elements,
  ab initio calculations on the way,
  allow estimation of theoretical uncertainties
- 2b currents modify (reduce) matrix elements,
  but it remains to be settled to what extent: ab
  initio calculations in lighter (toy) systems



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