Chiral Two-body Currents and Weak Decays

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Outline

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Nuclear weak decays

Nuclear weak processes play a major role in

- Astrophysics: Stellar evolution, Supernovae, Nucleosynthesis
- Nuclear structure: Gamow-Teller transitions, strength functions, Gamow-Teller resonance. . .
- Superallowed Fermi transitions:
  isospin symmetry breaking, CKM matrix unitarity. . .
- ^{3}H single-β decay: measurement of the neutrino mass (m_ν)
- Neutrinoless Double Beta Decay ($0\nu\beta\beta$):
  lepton number violation, Majorana character of neutrinos, information on m_ν
- . . .

Gamow-Teller quenching

Theoretical calculations need to “quench“ the Gamow-Teller coupling

$$\mathbf{J}_{n,1B} = g_A\,\sigma_n\tau_n^-\,, \qquad g_A^{\text{eff}} = q g_A, \qquad q \approx 0.75$$

to reproduce experimental lifetimes and strength functions
in regions where the spectroscopy is well reproduced

Shell Model

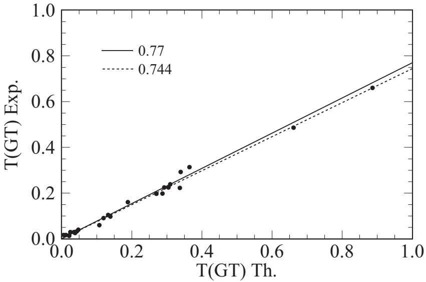
Wildenthal et al. PRC28 1343(1983)

Martínez-Pinedo et al. PRC53 2602(1996) $\Longrightarrow$

Energy Density Functional Methods

Bender et al. PRC65 054322(2002)

Rodríguez et al. PRL105 252503(2010)

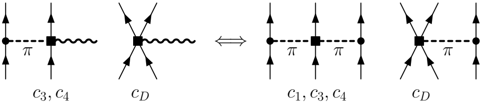


Problem approx. many-body method, incomplete operator, or both?

GT quenching and chiral EFT weak currents

This puzzle has been the target of many theoretical efforts:
Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...

Revisit in the framework of chiral effective field theory (chiral EFT)
Consistent description of nuclear forces and electroweak currents



Chiral EFT NN+3N forces recently applied to β decays:

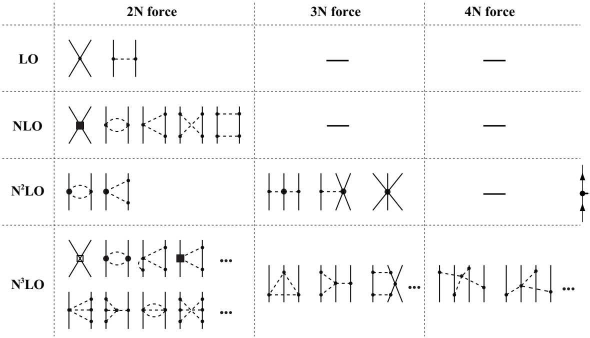
- ^{3}H β decay Gazit et al. PRL103 102502(2009), with consistent chiral 1B+2B currents
- ^{14}C β decay Maris et al. PRL106 202502(2011), standard 1B currents

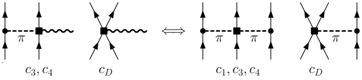
Chiral EFT

- Chiral EFT is a low energy approach to QCD
  valid for nuclear structure energies
- Enables a systematic basis for strong interactions,
  expansion in powers of Q/Λ_b
  $Q \sim m_\pi$, typical momentum scale
  $\Lambda_b \sim 500$ MeV, breakdown scale
- Nucleons interact via pion exchanges and contact interactions
- Provides consistent electroweak nuclear currents
- Short-range couplings are fitted to experiment (once)

Forces and Currents in Chiral EFT

- Systematic expansion: nuclear forces and electroweak currents

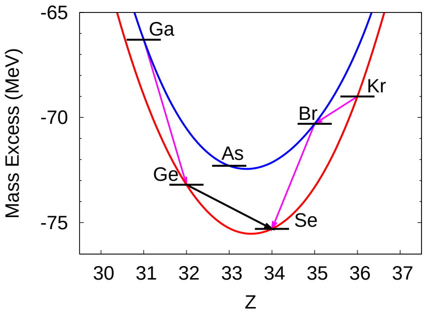




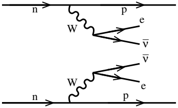
Same NN and 3N couplings

Application: Double beta decay

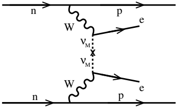
Double beta decay only appears when single-β decay is energetically forbidden or hindered by large J difference

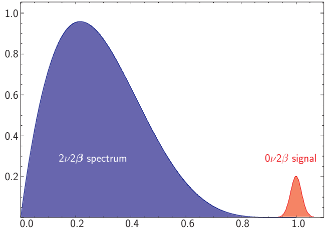


$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y



$T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y





Neutrinoless double beta decay and quenching

$0\nu\beta\beta$ decay needs also massive Majorana neutrinos ($\nu = \bar{\nu}$)
$\Rightarrow$ detection would proof Majorana nature of neutrinos

$$\left(T_{1/2}^{0\nu\beta\beta} \left(0^+ \rightarrow 0^+\right)\right)^{-1} = G_{01} \left|M^{0\nu\beta\beta}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$M^{0\nu\beta\beta}$ necessary to identify best candidates for experiment and to obtain neutrino masses and hierarchy with $m_{\beta\beta} = \left|\sum_k U_{ek}^2 m_k\right|$

Big $M^{0\nu\beta\beta}$ uncertainty due to g_A (quenched?) value: $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4$
Transferred momenta are high in $0\nu\beta\beta$ decay: $p \sim 100$ MeV
Is g_A also effectively quenched at $p \sim m_\pi$?

$0\nu\beta\beta$ candidates: medium-mass nuclei

Only candidates with $Q_{\beta\beta} > 2$ MeV are experimentally interesting

All the candidates medium-mass nuclei

Approximations will be required in the many-body method and the weak currents

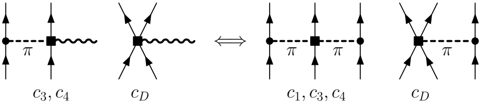
Transition	$Q_{\beta\beta}$ (MeV)	Ab. (%)
^{48}Ca → ^{48}Ti	4.274	0.2
^{76}Ge → ^{76}Se	2.039	8
^{82}Se → ^{82}Kr	2.996	9
^{96}Zr → ^{96}Mo	3.350	3
^{100}Mo → ^{100}Ru	3.034	10
^{110}Pd → ^{110}Cd	2.013	12
^{116}Cd → ^{116}Sn	2.802	7
^{124}Sn → ^{124}Te	2.288	6
^{130}Te → ^{130}Xe	2.530	34
^{136}Xe → ^{136}Ba	2.462	9
^{150}Nd → ^{150}Sm	3.667	6

Outline

Chiral weak currents

Chiral EFT currents Park et al. PRC67 055206(2003)
Systematically obtain the currents at Q^0, $Q^2\ldots$ order

- Order Q^0:
  - Fermi term: $J^0_n(p^2) = g_V(0)\,\tau^-_n$
  - Gamow-Teller term: $\mathbf{J}_{n,1B}(p^2) = g_A(0)\,\sigma_n\tau^-_n$
- Order Q^2:
  - $\frac{1}{m_N}$ terms
  - Loop corrections, pion propagator $\propto p^2$
- Order Q^3, two-body currents: $\mathbf{J}_{2B}\,(\text{Axial})$



Compare to phenomenological currents

Phenomenological weak nuclear currents
obtained from symmetry considerations

- Form-factors included via dipole parametrization
- Non-relativistic expansion up to $\frac{1}{m_N}$

Chiral $Q^0 + Q^2$ and phenomenological currents have same structure:

$$J^0_{n,1B}(p^2) = \tau_n^- \left[g_V(p^2)\right],$$
$$\mathbf{J}_{n,1B}(p^2) = \tau_n^- \left[g_A(p^2)\sigma_n - g_P(p^2)\frac{\mathbf{p}\,(\mathbf{p}\cdot\sigma_n)}{2m_N} + i\,(g_M + g_V)\,\frac{\sigma_n \times \mathbf{p}}{2m_N}\right].$$

(Different chiral p^2 and phenomenological dipole-like terms)

Systematic organization of 2B currents difficult in phenom. approach

Two-body currents in light nuclei

Two-body currents needed to reproduce data in light nuclei:

^{3}H β decay

Gazit et al. PRL103 102502(2009) $\Longrightarrow$

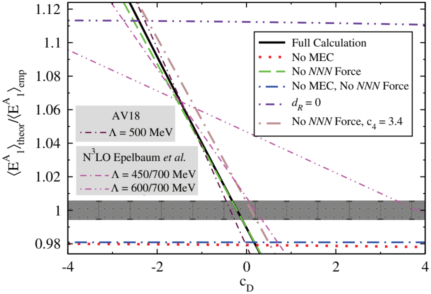
^{6}He β decay

Vaintraub et al. PRC79 065501(2009)

^{3}H μ capture

Gazit PLB666 472(2008)

Marcucci et al. PRC83 014002(2011)

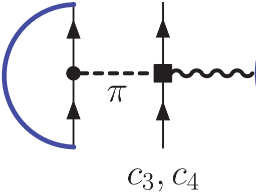


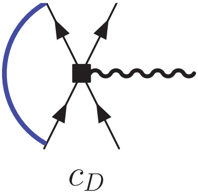
2B current contributions $\sim$ few % in light nuclei ($Q \sim \sqrt{BEm}$)

2B currents order Q^3 $\Rightarrow$ larger effect in medium-mass nuclei ($Q \sim k_F$)

Normal-ordered one-body current

- In order to estimate their effect on medium-mass nuclei take normal-ordered 1-body approximation with respect to Fermi gas,
- Sum over one nucleon, direct and the exchange terms





- $\Rightarrow \mathbf{J}^{\text{eff}}_{n,2B}$, normal-ordered (effective) one-body current
- Corrections are $\sim (n_{\text{valence}}/n_{\text{core}})$ in Fermi systems

Two-body currents

- The normal-ordered two-body currents are, neglecting (small) tensor-like terms

$$\mathbf{J}^{\text{eff}}_{n,2B} = -\frac{g_A\rho}{m_N f_\pi^2}\tau_n^-\sigma_n\left[F\left(\rho, c_3, c_4, c_D, p\right)\right],$$

$$F\left(\rho, c_3, c_4, c_D, p\right) = \frac{c_D}{g_A\Lambda_\chi} + \frac{2}{3}c_3\frac{\mathbf{p}^2}{4m_\pi^2+\mathbf{p}^2} + I(\rho, P)\left(\frac{1}{3}\left(2c_4 - c_3\right) + \frac{1}{6m_N}\right)$$

short-range   *p* dependent   long-range

- $\mathbf{J}^{\text{eff}}_{n,2B}$ only modifies the Gamow-Teller one-body current
- This is general for a spin-isospin symmetric reference state, in general there can be an additional orbital dependence

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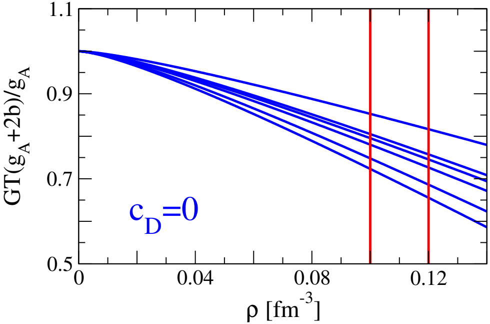
Two-body currents

- $\mathbf{J}^{\rm eff}_{n,2B}$ depends on couplings c_3, c_4, c_D and nuclear density ρ
- For density ρ consider the general range $0.10\ldots0.12$ fm^{-3}
- Couplings c_3, c_4 taken from NN potentials
  - From the N^{3}LO NN potentials:
    Entem et al. PRC68 041001(2003), Epelbaum et al. NPA747 362(2005)
  - From the PWA analysis:
    Rentmeester et al. PRC67 044001(2003)
  - Consider expected modification of couplings at next order:
    $\delta c_3 = -\delta c_4 \approx 1$ GeV^{-1}
  - $\Rightarrow$ Six sets of c_3, c_4 values considered in total

Long-range 2B currents and quenching

At $p = 0$ and $c_D = 0$ (long-range part of the currents only)
2B currents suppress 1B currents by $q = 0.85 \ldots 0.66$



⇒ Long-range 2B currents predict g_A quenching

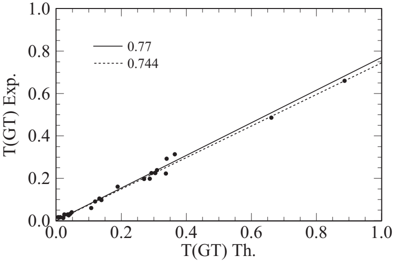
Short-range 2B currents and quenching I

Short-range part (c_D) not so well-known
$\Rightarrow$ Adjust c_D according to the empirical quenching required in Gamow-Teller transitions
$\Rightarrow$ compare to c_D values obtained by 3N fits

Extreme scenario (big quenching)

2B currents cause all g_A quenching suggested by theoretical calculations $g_A^{\mathrm{eff}} = q g_A$ due to the operator

$\Rightarrow$ contribution of the 2B currents
$q = 0.74$



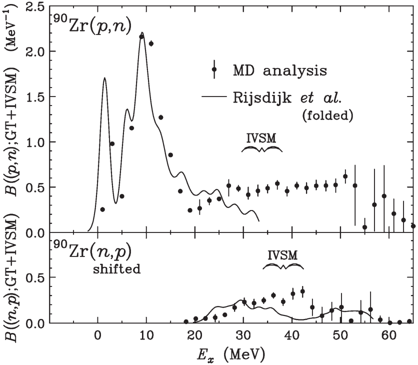
Short-range 2B currents and quenching II

Extreme scenario (small quenching)

2B currents responsible for small part of g_A quenching

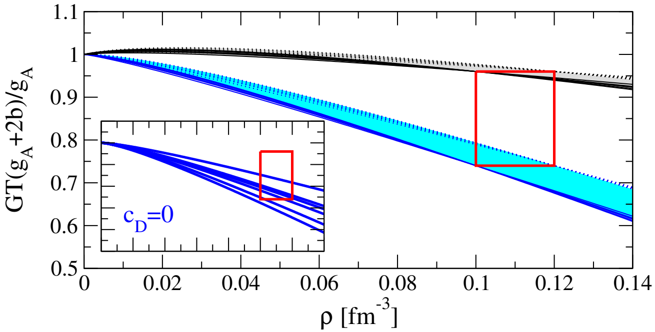
suggested by (much debated) strength function experimental extractions in ^{90}Zr up to high energies
Sasano et al. PRC79 024602(2009),
Yako et al. PLB615 193(2005)

$g_A^{\rm eff} = q g_A$ mainly
due to the many-body method
$\Rightarrow$ contribution of the 2B currents
$q = 0.96$



1B+2B currents constrained to GT quenching

We use $q = 0.74$ and $q = 0.96$ to constrain c_D



Allowed c_D lead to q values that lie inside the box

c_D from Gamow-Teller quenching

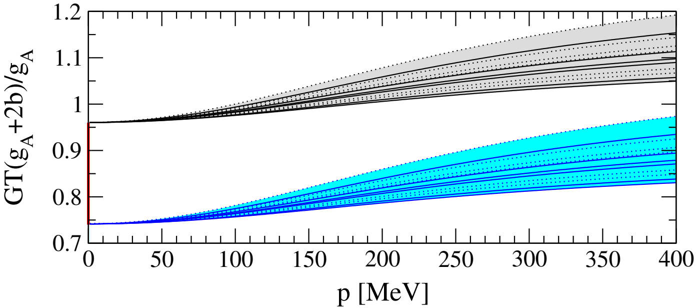
The sets of c_D values we find are

			$q = 0.74$	$q = 0.96$
	c_3	$2c_4 - c_3$	c_D from $\rho = 0.10 \dots 0.12$ fm^3	
EM	-3.2	14.0	$-0.17 \dots -0.70$	$-2.34 \dots -2.51$
EM+δc_i	-2.2	11.0	$0.40^* \dots -0.11$	$-1.78^* \dots -1.92$
EGM	-3.4	10.2	$0.55 \dots 0.04$	$-1.63 \dots -1.77$
EGM+δc_i	-2.4	7.2	$1.11 \dots 0.63$	$-1.06 \dots -1.18$
PWA	-4.78	12.7	$0.08 \dots -0.44^*$	$-2.10 \dots -2.26^*$
PWA+δc_i	-3.78	9.7	$0.64 \dots 0.14$	$-1.53 \dots -1.67$

- Using EM c_i's, $-0.3 \leq c_D \leq -0.1$ from ^{3}H BE and β decay fit favors empirical quenching scenario
- c_D values from fits to ^{3}H BE and ^{4}He radius also compatible with empirical quenching
- Small quenching $q = 0.96$ cannot be ruled out compatible with ^{3}H BE, ^{4}He radius fits in some cases (not EM)

1B+2B Gamow-Teller p dependence

The $\sigma\tau^-$ term, when two-body currents are included,
depends on transferred momentum p through the $\frac{2}{3}\, c_3\, \frac{\mathbf{p}^2}{4m_\pi^2+\mathbf{p}^2}$ term



Quenching gets weaker at $p \neq 0$
Typically $p \sim 100$ MeV $\sim m_\pi$ for $0\nu\beta\beta$ decay

Outline

$0\nu\beta\beta$ within the Chiral EFT approach

- Phenomenological currents have further uncertainty given by which terms in the current are kept in the calculation
- $\Rightarrow$ Chiral EFT currents can be systematically expanded: we can perform calculations to order Q^0, Q^2, Q^3 . . .
- In previous calculations of $0\nu\beta\beta$ big uncertainty in g_A^{eff}
  How relevant is it for transferred momenta $p \sim 100$ MeV?
- $\Rightarrow$ Chiral EFT predicts p dependence of g_A quenching

Calculation of $0\nu\beta\beta$ initial and final states

- Shell Model (SM) code NATHAN Caurier *et al.* RMP77 427(2005)
  State-of-the-art description of initial and final states
  by diagonalization of the full valence space
- SM interactions based on G matrices + MBPT (core polarization)
  with phenomenological monopole modifications
  (not yet consistent with the chiral currents)
- The valence spaces and interactions used are the following
  - *pf* shell for ^{48}Ca
    KB3 interaction
  - $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$ space for ^{76}Ge and ^{82}Se
    gcn.2850 interaction
  - $0g_{7/2}$, $1d_{3/2}$, $1d_{5/2}$, $2s_{1/2}$ and $0h_{11/2}$ space
    for ^{124}Sn, ^{130}Te and ^{136}Xe
    gcn.5082 interaction

Calculation of $0\nu\beta\beta$ transition operator

- The transition operator comes from the product of two currents

$$J_n^{\mu}(p^2)J_{m\mu}(p^2) = h^F(p^2)\Omega^F + h^{GT}(p^2)\Omega^{GT} + h^T(p^2)\Omega^T,$$

with Ω^F Fermi (1), Ω^{GT} Gamow-Teller ($\sigma_1\sigma_2$), Ω^T Tensor (S_{12})

$$\begin{aligned} h^F(p^2) &= h^F_{vv}(p^2), \\ h^{GT}(p^2) &= h^{GT}_{aa}(p^2) + h^{GT}_{ap}(p^2) + h^{GT}_{pp}(p^2) + h^{GT}_{mm}, \\ h^T(p^2) &= h^T_{ap}(p^2) + h^T_{pp}(p^2) + h^T_{mm} \end{aligned}$$

- Classify according to Chiral EFT expansion
  - Q^0: $h^{GT}_{aa}(0)$, $h^F_{vv}(0)$
  - Q^2: $h^{GT}_{aa}(p^2)$, $h^F_{vv}(p^2)$ plus all other terms
  - Q^3: Now $h^{GT}_{aa}(p^2)$, $h^{GT}_{ap}(p^2)$ have contribution from 2B currents

The $0\nu\beta\beta$ operator

The transition operator for $0\nu\beta\beta$ decay is:

$$M^{0\nu\beta\beta} = -\left(\frac{g_V(0)}{g_A(0)}\right)^2 M^F + M^{GT} - M^T$$

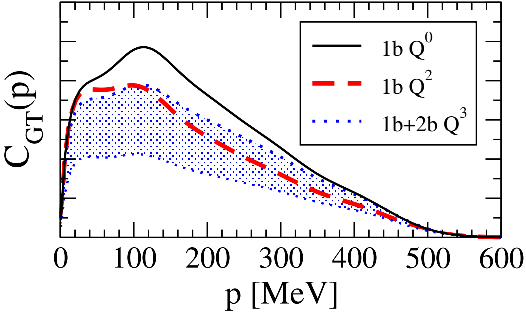
where $M^X = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- H^X(r)\, \Omega^X | 0_i^+ \rangle$

and $H^X(r) = \frac{2}{\pi} \frac{R}{g_A^2(0)} \int_0^\infty f^X(qr) \frac{h^X(q)}{\left(q + E_a^m - \frac{1}{2}(E_i - E_f)\right)} q\, dq$

Obtain $M^{0\nu\beta\beta}$ including chiral EFT 1B+2B currents
These terms should be included in any calculation of the NMEs (SM, EDF, QRPA, IBM...)

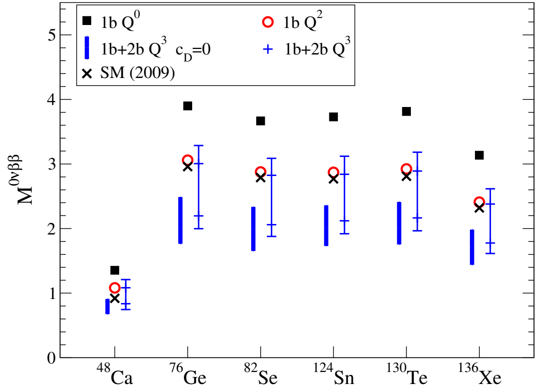
1B+2B *p* dependence

Check transferred momenta $p \sim m_\pi$ dominate the NME, true at different orders Q in the calculation



where $M^{0\nu\beta\beta} = \int_0^\infty C(p)dp$

1B+2B Nuclear Matrix Elements



Order Q^2 similar to phenomenological currents

Long-range Q^3 predicts NME $\sim$ 35% reduction
They are order Q^2 in Chiral EFT with explicit Deltas

Effect of 2B currents Q^3 ranges from +10% to -35% of the NME
(Smaller than -45% expected by $q^2 = 0.74^2$ due to $p \neq 0$)

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Summary and Outlook: 2B weak currents

- Chiral EFT weak currents give two-body contributions at Q^3
- 2B currents modify Gamow-Teller $(\sigma\tau^-)$ term
  - The long range 2B currents predict g_A quenching
  - p dependence of the quenching is also predicted
- Nuclear Matrix Elements for $0\nu\beta\beta$ decay modified $-35\ldots10\%$ by chiral 2B currents
- Outlook
  - Beyond one-body approximation of 2b currents
  - Study other electroweak decays: M1 transitions...
  - Treat consistently interaction and currents (operators)