Neutrinoless Double Beta Decay (and more) within the Interacting Shell Model

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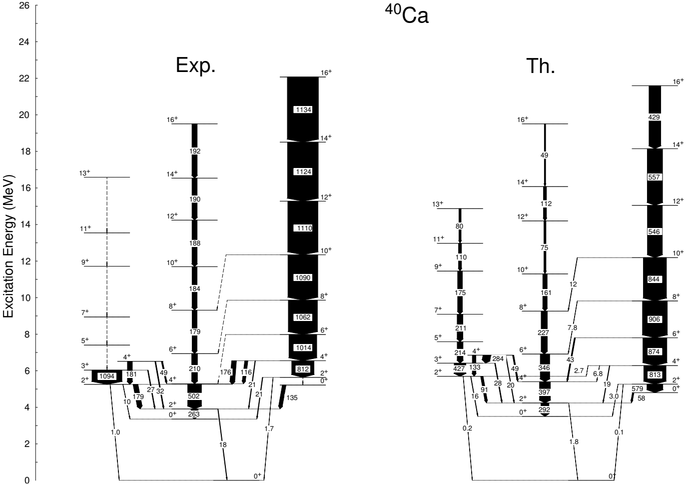
"Shell Model as a Unified View of Nuclear Structure"
in honour to Etienne Caurier, Alfredo Poves and Andrés Zuker

Strasbourg, 10 October 2012

Spherical, deformed, superdeformed bands in ^{40}Ca



Outline

1 Introduction

2 $0\nu\beta\beta$ decay
- Initial and Final states
- Transition currents

3 Spin-Dependent WIMP-nucleus scattering

4 Summary and Outlook

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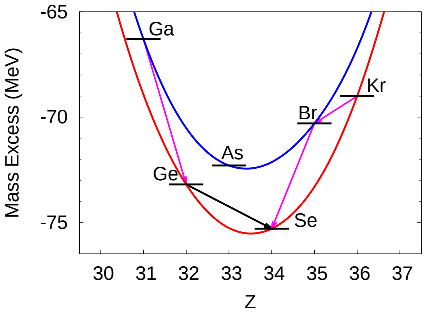
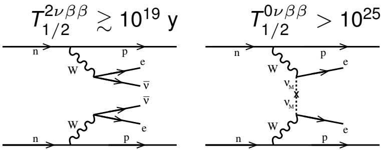
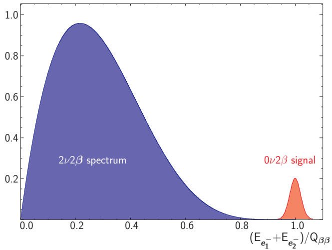
1. Introduction
2. $0\nu\beta\beta$ decay
   - Initial and Final states
   - Transition currents
3. Spin-Dependent WIMP-nucleus scattering
4. Summary and Outlook

Double beta decay

Double beta decay is a second-order process which appears when single-β decay is energetically forbidden or hindered by large ΔJ







Neutrinoless double beta decay

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

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

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

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

- Many-body method to describe initial and final nuclear states
- Transition operator, appropriate for this decay

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

Only candidates with
$Q_{\beta\beta} > 2$ MeV
are experimentally interesting
(very slow process)

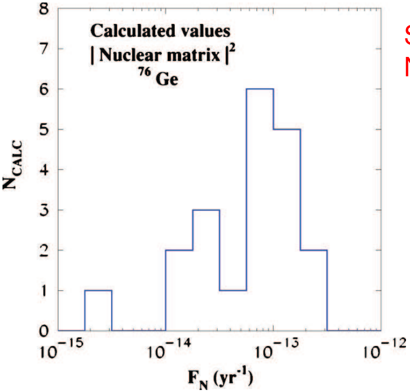
All the candidates
medium-mass nuclei $\Rightarrow$
use Shell Model as
many-body method

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

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
- 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

Nuclear Matrix Elements: 2003



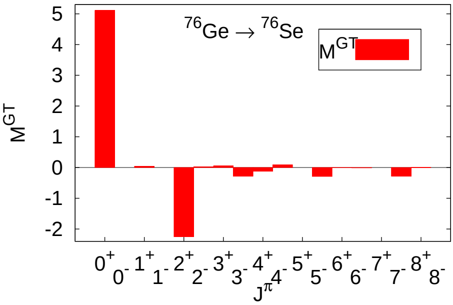
Strong disagreement in calculations of Nuclear Matrix Elements (NMEs)

The uncertainty in the calculated nuclear matrix elements for neutrinoless double beta decay will constitute the principal obstacle to answering some basic questions about neutrinos. The essential problem is that the correct theory of nuclei

Bahcall, Murayama, Peña-Garay
PRD70 033012 (2004)

Pair structure of the NME

- To study the role of pairing like correlations in the $0\nu\beta\beta$ decay we write the operator as: $\hat{M}^{0\nu\beta\beta} = \sum_{J^\pi} \hat{P}^\dagger_{J^\pi} \hat{P}_{J^\pi}$
- The NME as a function of the J^P of the decaying pair is:



- The leading contribution comes from 0^+ pairs
- The other J^P terms go in the opposite direction, tend to reduce the NME

Caurier, JM, Nowacki, Poves PRL100 052503 (2008)

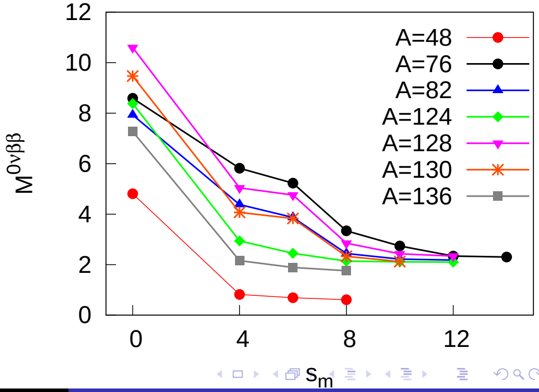
Seniority structure of the NME

Consequently, pairing like correlations seem to favour the $0\nu\beta\beta$ decay

Decompose our wave functions in terms of the seniority, the number of particles not being part of coupled pairs

$$|0_i^+\rangle = \sum_s \alpha_s |s\rangle_i$$

$$|0_f^+\rangle = \sum_s \beta_s |s\rangle_f$$



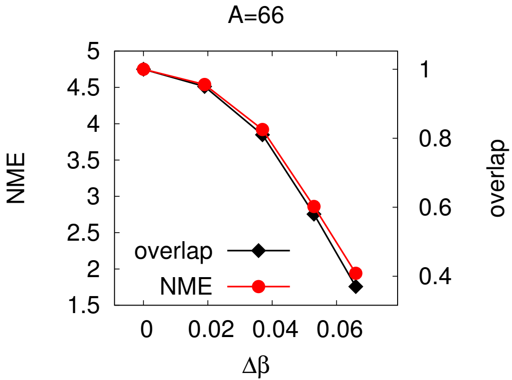
High seniority components (correlations) significantly reduce the NME!

Caurier, JM, Nowacki, Poves
PRL100 052503 (2008)

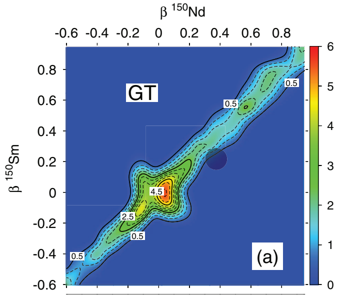
Deformation and $0\nu\beta\beta$ decay

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

It is very suppressed when nuclei have different structure



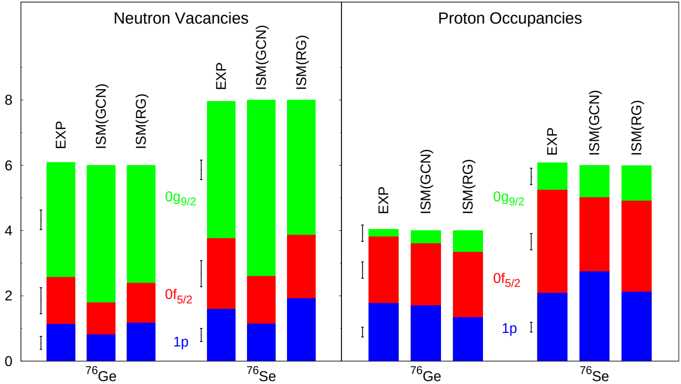
JM, Caurier, Nowacki, Poves
JPCS267 012058 (2011)



Rodríguez, Martínez-Pinedo
PRL105 252503 (2010)

$A = 76$ Occupancies

Experimental occupancies are reproduced



$M^{0\nu\beta\beta} =$
2.81 (GCN)
3.26 (RG)

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

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

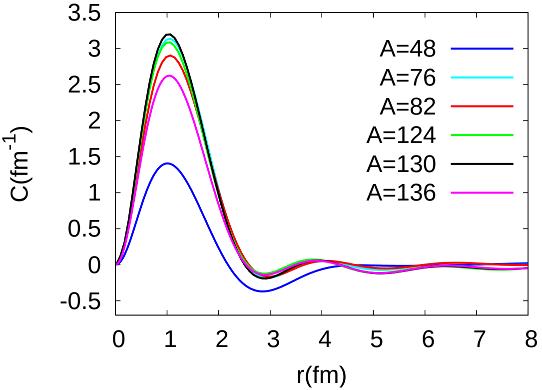
Radial behaviour of the NME

$$M^{0\nu\beta\beta} = \int_0^\infty C(r)dr$$

Maximum around 1 fm

Almost no contribution after 3 fm
Only nucleons close to each other contribute

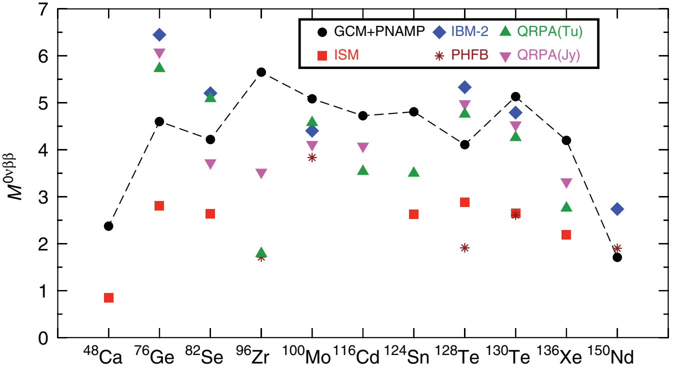
Typical transferred momenta
$p \sim 100 - 200$ MeV



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

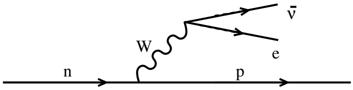
Nuclear Matrix Elements

Finally, spread $\sim$ factor 2 in the different calculations of the NMEs



Rodríguez, Martínez-Pinedo PRL105 252503 (2010)

Gamow-Teller quenching



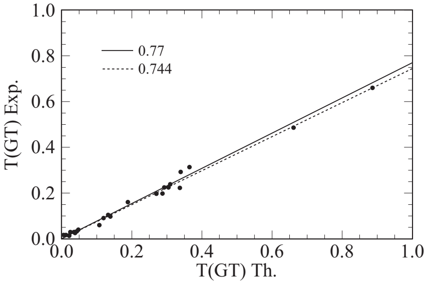
$$\mathbf{J}_{n,1B} = g_A \, \sigma_n \tau_n^- , \quad g_A^{\text{eff}} = q g_A , \quad q \approx 0.75$$

Theory needs to “quench“ Gamow-Teller coupling to reproduce experimental lifetimes and strength functions 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)

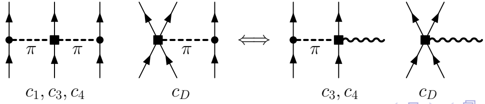
Problem approx. many-body method, incomplete operator, or both?

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...

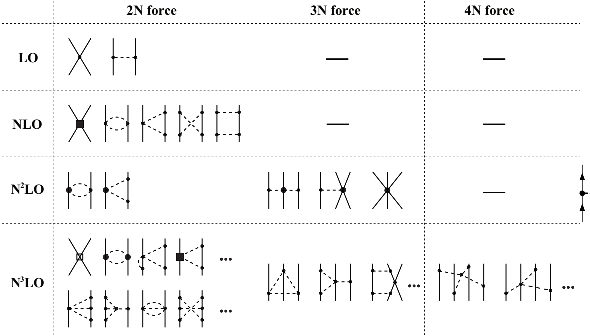
Major $M^{0\nu\beta\beta}$ uncertainty:
g_A (quenched?) value: $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4$
Transferred momenta are high in $0\nu\beta\beta$ decay: $p \sim 100$ MeV
Is g_A also effectively quenched at $p \sim 100$ MeV?

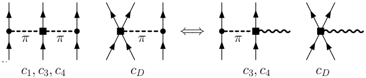
Revisit in the framework of chiral effective field theory (chiral EFT)
Consistent description of nuclear forces and electroweak currents



Forces and Currents in Chiral EFT

Systematic expansion: nuclear forces and electroweak currents





Same NN and 3N couplings

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

Chiral weak currents

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

Order Q^0: Fermi term: $J_n^0(p^2) = g_V(0)\,\tau_n^-$

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 $\propto p^2$

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

$$J^0_{n,1B}(p^2) = \tau_n^- \left[g_V(p^2)\right],$$

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

Order Q^3: Two-body currents: $\mathbf{J}_{2B}\,(\mathrm{Axial})$

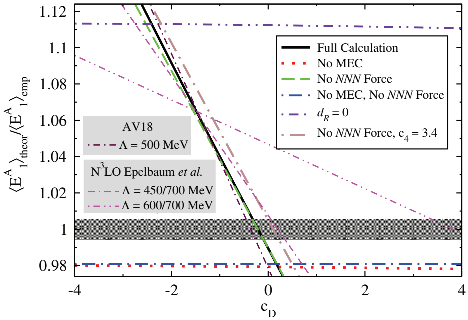
Two-body currents in light nuclei

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

^{3}H β decay
Gazit, Quaglioni, Navrátil
PRL103 102502(2009) $\Longrightarrow$

^{6}He β decay
Vaintraub, Barnea, Gazit
PRC79 065501(2009)

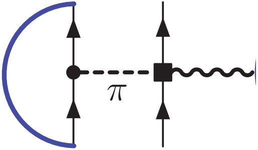
^{3}H μ capture
Gazit PLB666 472(2008)
Marcucci et al. PRC83 014002(2011)



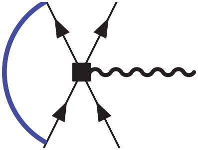
2B current contributions $\sim$ few % in light nuclei ($Q \sim \sqrt{BEm}$)
2B currents order Q^3 $\Rightarrow$ larger effect in medium-mass nuclei ($Q \sim k_F$)

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



c_3, c_4



c_D

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

Two-body currents: modification of Gamow-Teller

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

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

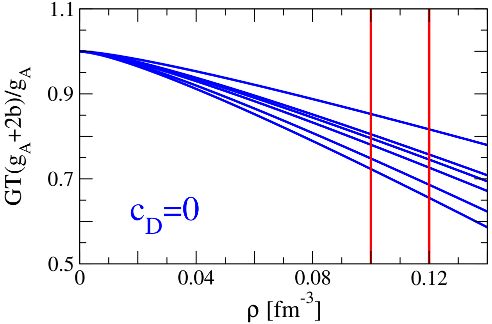
$$F\left(\rho, c_3, c_4, c_D, p\right) = \frac{c_D}{g_A \Lambda_\chi} + \frac{2}{3} c_3 \frac{\mathbf{p}^2}{4m_\pi^2 + \mathbf{p}^2} + I(\rho, P)\left(\frac{1}{3}\left(2c_4 - c_3\right) + \frac{1}{6m_N}\right)$$

short-range p dependent long-range

- $\mathbf{J}^{\mathrm{eff}}_{n,2B}$ 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

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 $q = 0.85...0.66$



- For density ρ consider the general range $0.10 \ldots 0.12$ fm^{-3}
- Couplings c_3, c_4 taken 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}

$\Rightarrow$ Long-range 2B currents predict g_A quenching

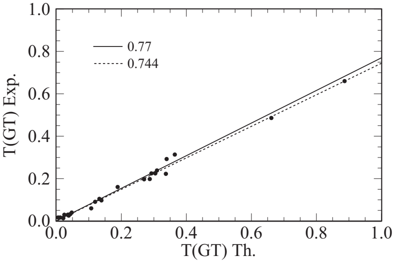
Short-range 2B currents and quenching I

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 $g_A^{\text{eff}} = qg_A$ due to the operator

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



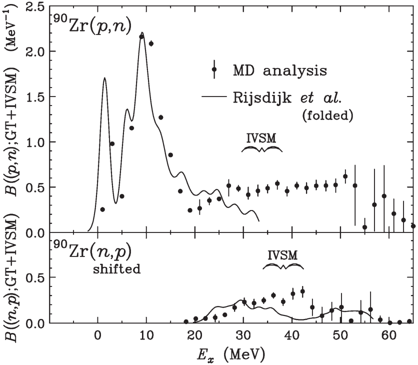
Short-range 2B currents and quenching II

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)

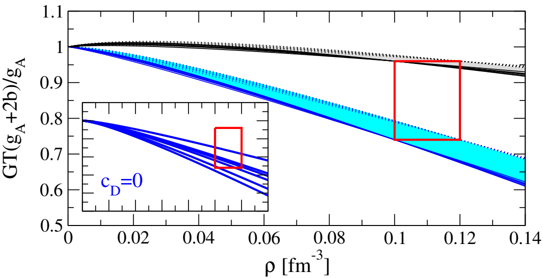
$g_A^{\text{eff}} = q g_A$ mainly
due to the many-body method
$\Rightarrow$ contribution of the 2B currents
$q = 0.96$



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



JM, Gazit, Schwenk PRL107 062501 (2011)

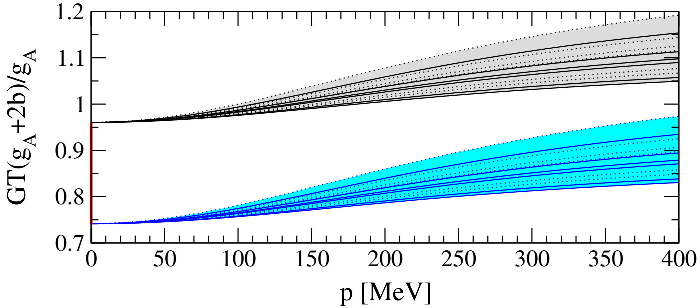
Using EM c_i's, $-0.3 \leq c_D \leq -0.1$ from ^{3}H BE and β decay fit favors empirical quenching

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



JM, Gazit, Schwenk PRL107 062501 (2011)

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

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

- The transition operator comes from the product of two currents

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

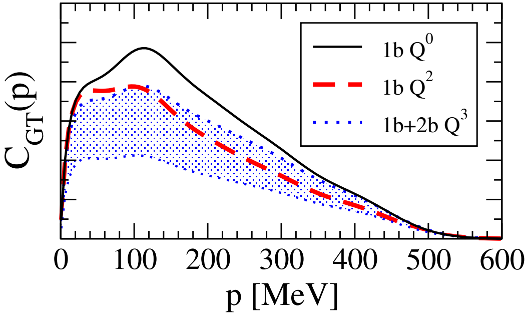
with Ω^F Fermi (1), Ω^{GT} Gamow-Teller $(\sigma_1\sigma_2)$, Ω^T Tensor (S_{12})

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

- 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

1b+2b *p* dependence

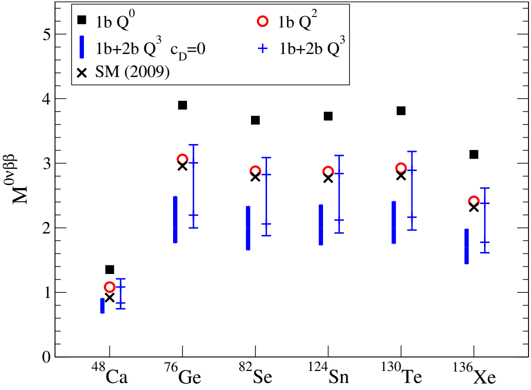
Check which transferred momenta ∼100 MeV dominate the NME, at different orders *Q* in the chiral expansion



JM, Gazit, Schwenk PRL107 062501 (2011)

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

1B+2B Nuclear Matrix Elements



JM, Gazit, Schwenk PRL107 062501 (2011)

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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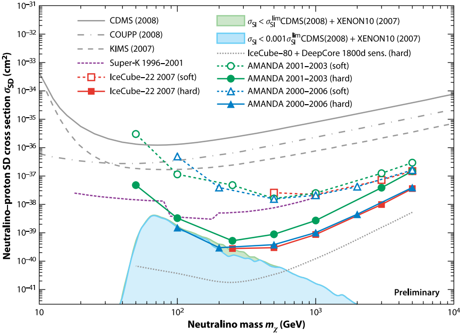
Dark Matter

Some rarely interacting, massive, non-baryonic, kind of matter that represents $\sim$ 23% of the energy in the Universe: Dark Matter

Best candidates are WIMPs (weakly interacting massive particles), eg neutralinos in supersymmetric (SUSY) particle physics models



Feng ARAA48 495 (2010)

Indirect evidence $\Rightarrow$ challenge is direct detection of Dark Matter

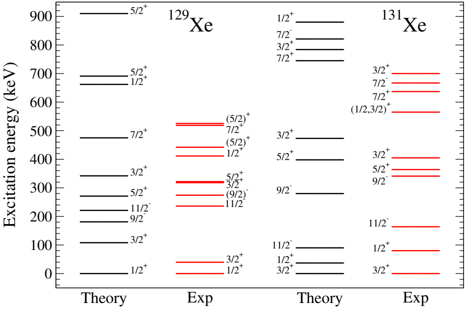
Put big amount of material (like in $0\nu\beta\beta$ decay), search WIMP-matter signal WIMP-nucleus signal!

Shell Model for Dark Matter detection

The Shell Model can be applied to direct cold dark matter searches

For spin-dependent WIMP scattering off nuclei

$$\frac{d\sigma}{dp^2} = \frac{8G_F^2}{(2J+1)v^2} S_A(p), \quad S_A(p) = \sum_L \left(\left|\langle J || \mathcal{T}_L^{\mathrm{el}\,5}(p) || J \rangle\right|^2 + \left|\langle J || \mathcal{L}_L^5(p) || J \rangle\right|^2 \right)$$



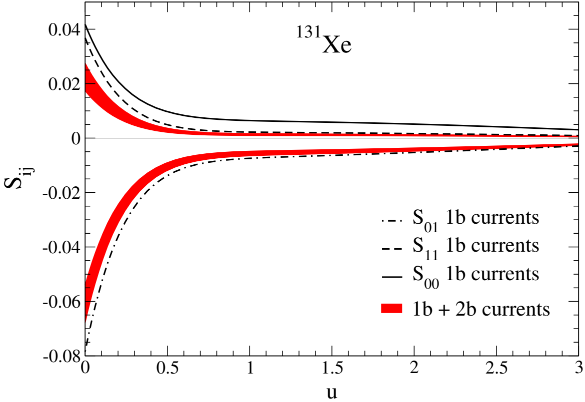
JM, Gazit, Schwenk arXiv:1208.109 (2012)

Isotopes ^{129}Xe and ^{131}Xe for liquid Xenon detectors, which provide most stringent experimental limits

Calculations in the $0g_{7/2}$, $1d_{3/2}$, $1d_{5/2}$, $2s_{1/2}$ and $0h_{11/2}$ valence space using the gcn.5082 interaction

Spin-dependent WIMP scattering off nuclei

The same techniques can be applied to different (but analogue) chiral EFT currents: WIMP-induced nuclear currents



JM, Gazit, Schwenk arXiv:1208.109 (2012)

$S_A(p) = a_0^2 S_{00} + a_0 a_1 S_{01} + a_1^2 S_{11}$

Leading chiral 2b currents reduce the isovector nuclear response functions (structure factors) $\sim 25 - 55\%$

Similar reduction for ^{129}Xe

Outline

1 Introduction

2 $0\nu\beta\beta$ decay
- Initial and Final states
- Transition currents

3 Spin-Dependent WIMP-nucleus scattering

4 Summary and Outlook

Summary and Outlook

- Shell Model gives good description of initial and final states of $0\nu\beta\beta$ decay: includes and explains the role of pairing and deformation correlations
- Chiral 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 $-35\ldots10\%$
- Application to spin-dependent WIMP-nucleus scattering relevant for Dark Matter direct detection
- **Outlook**
    - Perform Shell Model calculations in larger valence spaces
    - Beyond one-body approximation of 2b currents
    - Treat consistently interaction and currents (operators)