Matrix Elements for Fundamental Symmetries: Neutrinoless Double Beta Decay WIMP Scattering off Nuclei

Javier Menéndez

Institut für Kernphysik (TU Darmstadt) and ExtreMe Matter Institute (GSI)

Nuclei and Fundamental Symmetries:
Theory Needs of Next-Decade Experiments

INT, Seattle, 12 August 2013

TECHNISCHE UNIVERSITÄT DARMSTADT

Collaborators

TECHNISCHE UNIVERSITÄT DARMSTADT

P. Klos, G. Martínez-Pinedo,
T. R. Rodríguez, A. Schwenk

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

D. Gazit

UAM UNIVERSIDAD AUTONOMA DE MADRID

A. Poves

Outline

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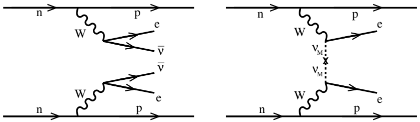
1. Neutrinoless double-beta decay

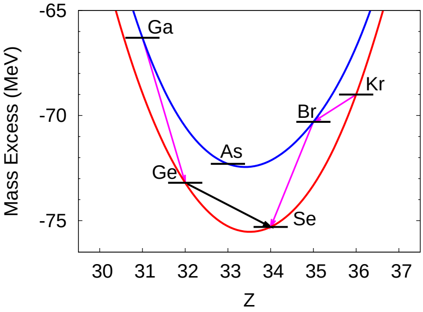
2. WIMP scattering off nuclei

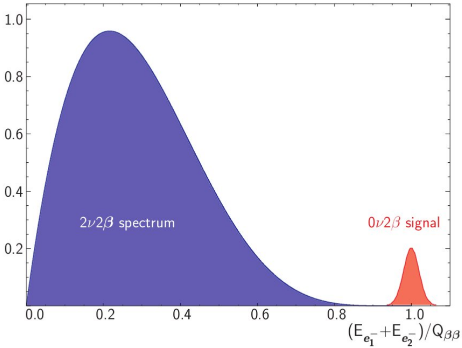
Double beta decay

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

$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y $\qquad T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y







Neutrinoless double beta decay

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

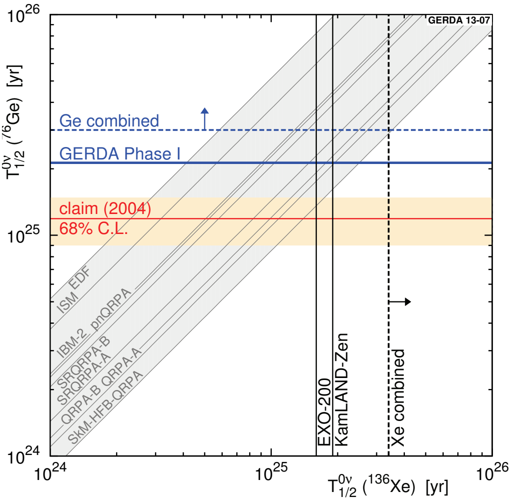
$$\left(T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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

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

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

Nuclear Matrix Element Uncertainty



GERDA Collaboration arXiv:1307.4720 (2013)

Nuclear Matrix Elements crucial to extract information from experiment

Different NME calculations give results very spread

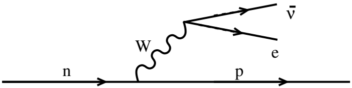
How can we understand these differences?

Study transition operator and many-body nuclear structure

$M^{0\nu\beta\beta}$ uncertainty: quenching

Major $M^{0\nu\beta\beta}$ uncertainty is g_A (quenched?) value:

$M^{0\nu\beta\beta} \propto g_A^2 \Rightarrow \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4$



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

Theory needs to “quench“ Gamow-Teller coupling to reproduce experimental lifetimes and strength functions where the spectroscopy is well reproduced

Wildenthal et al. PRC28 1343(1983)
Martínez-Pinedo et al. PRC53 2602(1996)
Bender et al. PRC65 054322(2002)
Rodríguez et al. PRL105 252503(2010)

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 EFT) currents

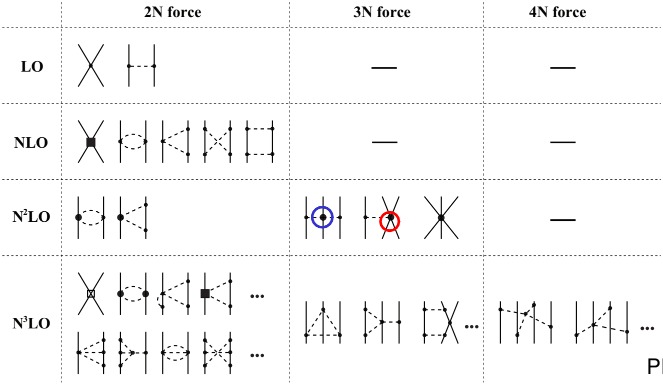
Transferred momenta are high in $0\nu\beta\beta$ decay: $p \sim 100$ MeV

Is anything missing in the transition operator?

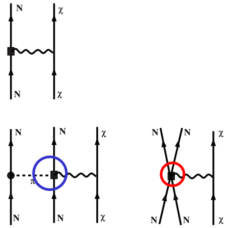
Forces and Currents in Chiral EFT

Systematic expansion: nuclear forces and hadronic currents

Forces and Currents depend on same couplings



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



JM, Gazit, Schwenk
PRD86 103511(2012)

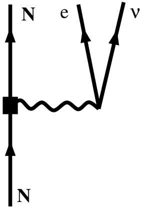
Hadronic 1b currents in chiral EFT

Chiral EFT provides systematic expansion of hadronic electroweak currents

Corrections to standard currents (transition operator)
are more controlled than based on phenomenology

At lowest orders Q^0 and Q^2
there is one-body (1b) currents

Same expressions obtained
using phenomenological arguments
Šimkovic et al. PRC60 055502(1999)



$$J_i^0(p) = g_V(p^2)\tau^-, \qquad \boldsymbol{J}_i(p) = \left[g_A(p^2)\boldsymbol{\sigma} - g_P(p^2)\frac{(\boldsymbol{p}\cdot\boldsymbol{\sigma}_i)\boldsymbol{p}}{2m} + i\,(g_M + g_V)\,\frac{\boldsymbol{\sigma}_i \times \boldsymbol{p}}{2m}\right]\tau^-,$$

$$g_V(p^2) = g_V\,(1 - 2\frac{p^2}{\Lambda_V^2}), \qquad g_A(p^2) = g_A\,(1 - 2\frac{p^2}{\Lambda_A^2}),$$

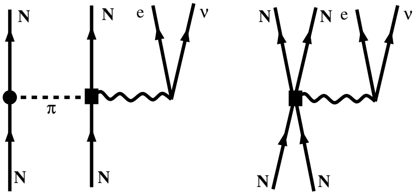
$$g_P(p^2) = \frac{2g_{\pi pn}F_\pi}{m_\pi^2 + p^2} - 4\,g_A(p^2)\frac{m}{\Lambda_A^2}, \qquad g_M = \kappa_p - \kappa_n = 3.70,$$

Hadronic 2b currents in chiral EFT

At order Q^3 chiral EFT predicts contributions from two-body (2b) currents

Reflect interactions between nucleons

Long-range currents dominant



Park et al. PRC67 055206(2003)

$$\mathbf{J}_{12}^{3} = -\frac{g_A}{4F_\pi^2}\frac{1}{m_\pi^2+k^2}\Big[2\Big(c_4+\frac{1}{4m}\Big)\mathbf{k}\times(\sigma_\times\times\mathbf{k})\tau_\times^3 + 4c_3\mathbf{k}\cdot(\sigma_1\tau_1^3+\sigma_2\tau_2^3)\mathbf{k} - \frac{i}{m}\mathbf{k}\cdot(\sigma_1-\sigma_2)\mathbf{q}\tau_\times^3\Big]$$

Long-range currents depend on c_3, c_4 couplings of nuclear forces

Leading 2b currents are predicted

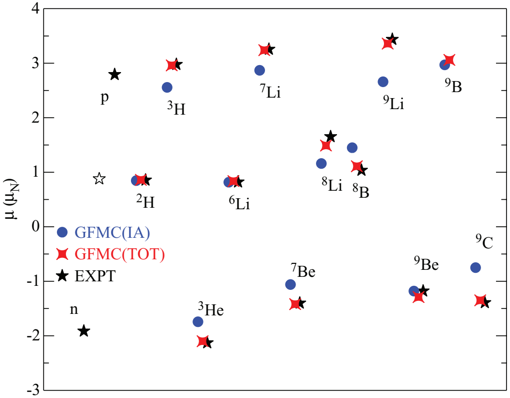
Two-body currents in light nuclei

2b currents (Meson-exchange currents)
needed to reproduce data in *ab initio* calculations of light nuclei:

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

$A \leq 9$ magnetic moments
Pastore et al. PRC87 035503(2013)
$\Longrightarrow$

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

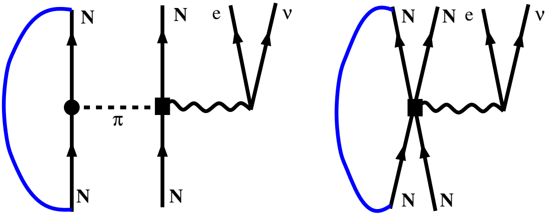


2b current contributions $\sim$ few % in light nuclei ($Q \sim \sqrt{BEm}$)
2b currents order $Q^3 \Rightarrow$ larger effect in medium-mass nuclei ($Q \sim k_F$)

2b currents: normal-ordering

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

Sum over one nucleon, direct and the exchange terms



$\Rightarrow \mathbf{J}^{\rm eff}_{n,2b}$, normal-ordered (effective) one-body current

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

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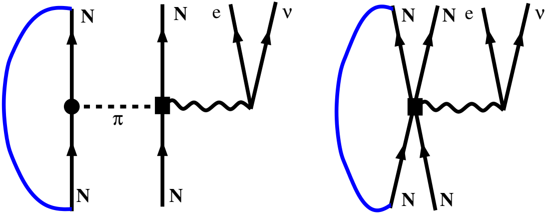

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The normal-ordered two-body currents modify GT operator

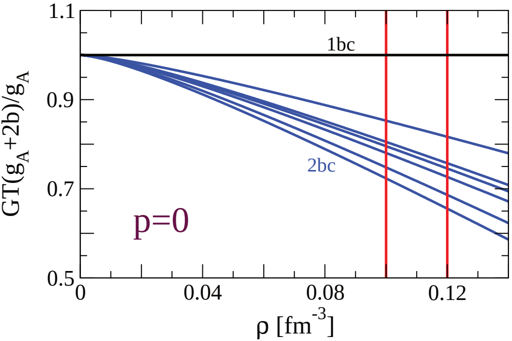
$$\mathbf{J}^{\text{eff}}_{n,2b} = -\frac{g_A \rho}{f_\pi^2} \tau_n^- \sigma_n \left[\frac{2}{3} c_3 \frac{\mathbf{p}^2}{4m_\pi^2 + \mathbf{p}^2} + I(\rho, P) \left(\frac{1}{3} (2c_4 - c_3) + \frac{1}{6m_N} \right) \right],$$

long-range p dependent   long-range p independent

Contribution of 2b currents

2b currents at $p = 0$: GT decays, $2\nu\beta\beta$ decay

$$\mathbf{J}^{\text{eff}}_{n,2b} = -\frac{g_A \rho}{f_\pi^2} \tau_n^- \sigma_n \left[I(\rho, P) \left(\frac{1}{3} (2c_4 - c_3) + \frac{1}{6m_N} \right) \right],$$



JM, Gazit, Schwenk PRL107 062501 (2011)

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

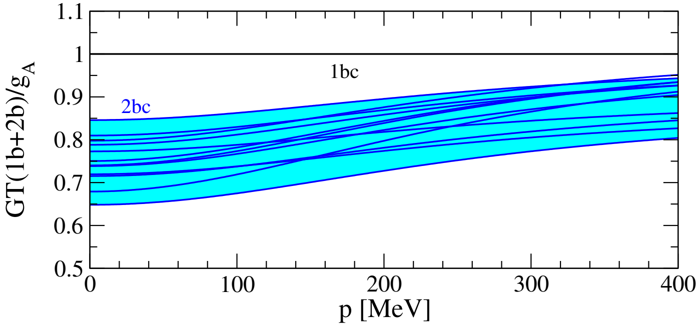
Couplings c_3, c_4 from NN potentials
Entem et al. PRC68 041001(2003)
Epelbaum et al. NPA747 362(2005)
Rentmeester et al. PRC67 044001(2003)
$\delta c_3 = -\delta c_4 \approx 1$ GeV^{-1}

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

Transferred-momentum dependence

The $\sigma\tau^-$ term depends on transferred momentum p:

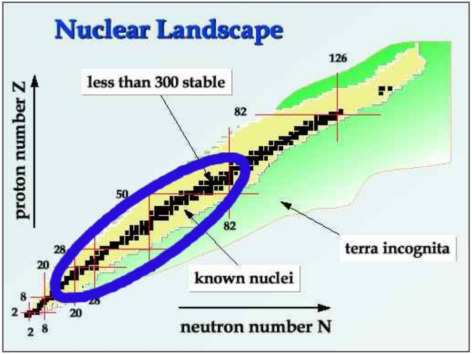
$$-\frac{g_A\rho}{f_\pi^2}\tau_n^-\sigma_n\frac{2}{3}\,c_3\,\frac{\mathbf{p}^2}{4m_\pi^2+\mathbf{p}^2}$$



JM, Gazit, Schwenk PRL107 062501 (2011)

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

Nuclear Structure approach

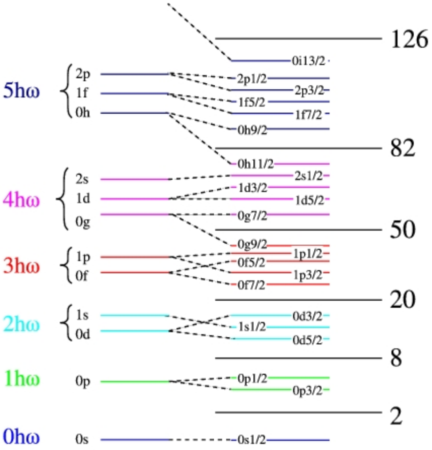


Big variety of nuclei in the nuclear chart, $A \sim 2...300$

Systematic *ab initio* calculations only possible in the lightest nuclei

Poses a hard many-body problem: design approximate methods suited for different regions

Interacting Shell Model:
Solve the problem choosing the (more) relevant degrees of freedom
Use realistic nucleon-nucleon (NN) and three-nucleon (3N) interactions



Chose as basis states that of the 3D Harmonic Oscillator

To keep the problem feasible, the configuration space is separated into

- Outer orbits:
  orbits that are always empty
- Valence space: the space in which we explicitly solve the problem
- Inner core:
  orbits that are always filled

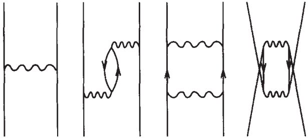
$$\mathrm{Dim} \sim \begin{pmatrix} (p+1)(p+2)_\nu \\ N \end{pmatrix} \begin{pmatrix} (p+1)(p+2)_\pi \\ Z \end{pmatrix}$$

Solving the Schrödinger equation

Now, we have to solve the nuclear problem in the valence space,

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

where H_{eff} is obtained in many-body perturbation theory includes the effect of inner core and outer orbits



The many body wave function will be a linear combination of the Slater Determinants built upon these single particle states

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

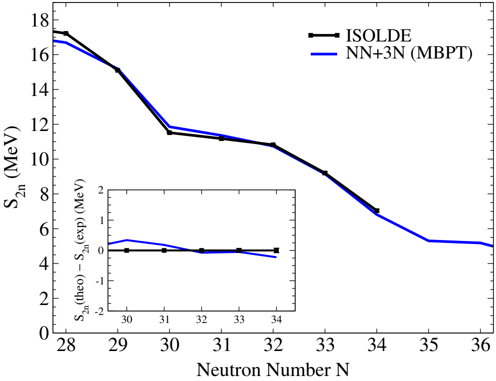
The ISM codes Antoine/Nathan diagonalize up to 10^{10} Slater determinants

Caurier *et al.* RMP 77 (2005)

Nuclear Structure with Chiral EFT: calcium

Ca isotopes (on top of ^{40}Ca core)

Compare $S_{2n} = -[B(N,Z) - B(N-2,Z)]$ with experiment



Gallant et al. PRL 109 032506 (2012)

Wienholtz et al. Nature 498 346 (2013)

Precision measurements with TITAN changed AME 2003 $\sim$ 1.74 MeV in ^{52}Ca

Very recently ^{53,54}Ca measured at ISOLDE: $N = 32$ magic number

Excellent agreement between calculation and experiment (Similar to phenomenological ISM interactions)

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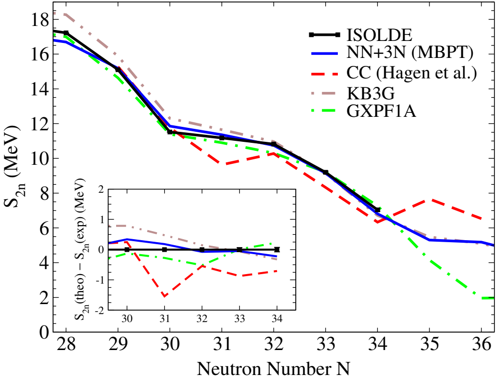

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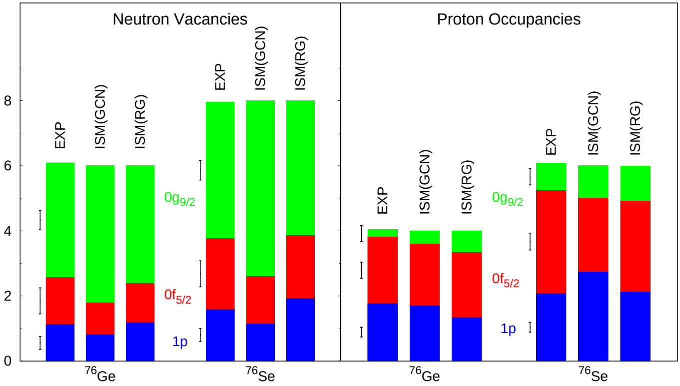
Calculation of $0\nu\beta\beta$ initial and final states

- 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

Test of nuclear structure: occupancies of ^{76}Ge, ^{76}Se

Experimental occupancies are well described!



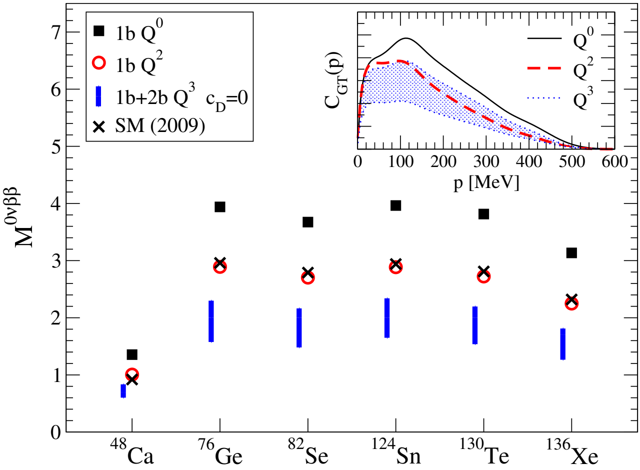
Calculations using state-of-the-art ISM interactions and valence spaces (NATHAN code)

$M^{0\nu\beta\beta}$ =
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)

Nuclear Matrix Elements for $0\nu\beta\beta$ decay



JM, Gazit, Schwenk PRL107 062501 (2011)

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

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

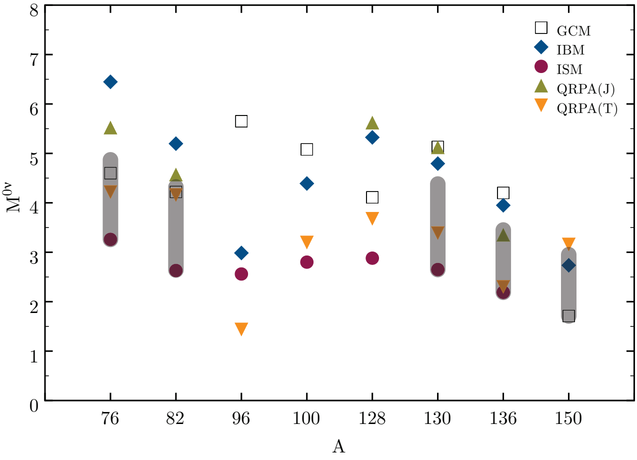
At order Q^3 2b currents reduce $\sim$ 15% – 40% the NME

Smaller than -45% ($q^2 = 0.75^2$) due to momentum-transfer $p > 0$

2b currents to be included by any many-body method computing $0\nu\beta\beta$ decay

$M^{0\nu\beta\beta}$ uncertainty: nuclear structure

Different calculations differ factor $\sim$ 2 remain:
Correction to the transition operator affect all NME calculations



ISM and EDF very different results

How can we understand these differences?

Gomez-Cadenas et al., JCAP06 007(2011)

Non-physical transitions (except ^{48}Ca) in the *pf* shell

Non-physical transitions in the *pf* shell

- ISM and EDF very well tested in this region
- ISM calculation with spin-orbit partners (Ikeda Sum Rule fulfilled)

Gamow-Teller part of the NME: $M_{GT}^{0\nu\beta\beta}$

- Dominant part of the NME
- Avoids problems with good isospin in EDF ($M_{F}^{0\nu\beta\beta}$ overestimated)

Study different decay chains:

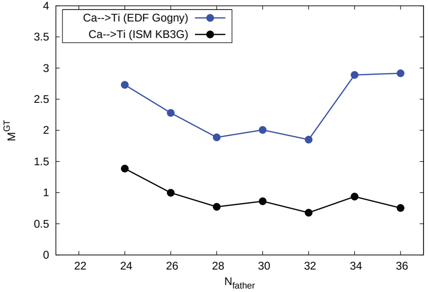
- Ca$\rightarrow$Ti, Ti$\rightarrow$Cr, Cr$\rightarrow$Fe, Fe$\rightarrow$Ni
- Protons expected to be dominantly in the $f_{7/2}$ orbital
- Neutrons lighter isotopes mainly $f_{7/2}$ orbital,
  in heavier isotopes also $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ orbitals

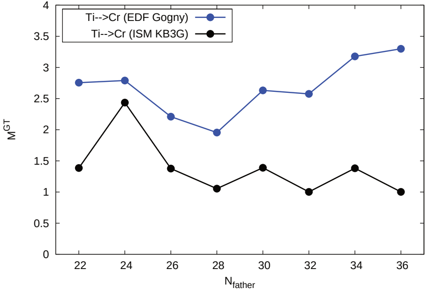
NME systematics in the *pf* shell

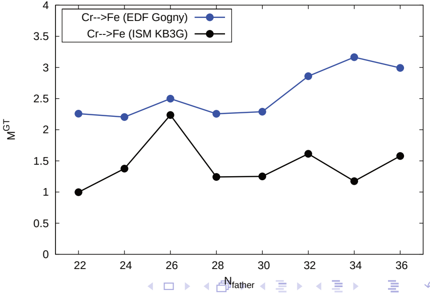
Trends in $M^{0\nu\beta\beta}_{GT}$, related to structure: closed shells, mirror nuclei similarly reproduced

In same region, relative matrix elements better constrained

ISM systematically below EDF for any nuclear interaction







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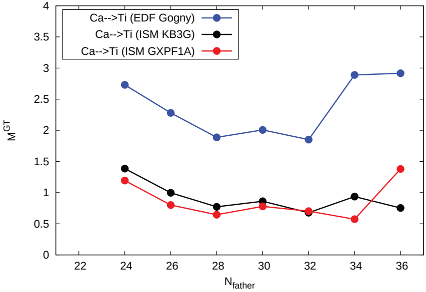
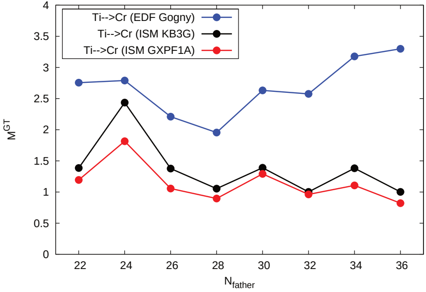
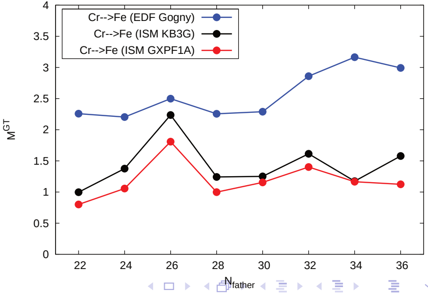


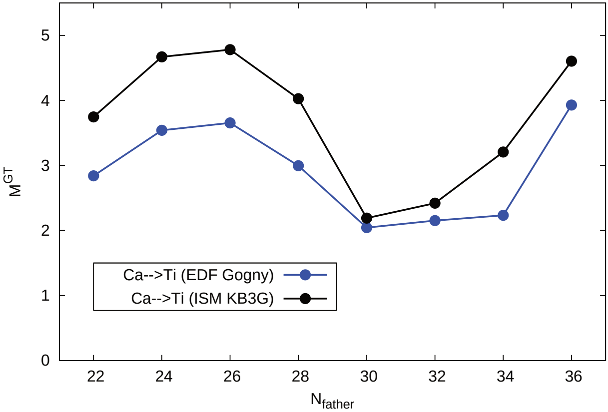




NME systematics in the *pf* shell: spherical case

Non-realistic spherical initial and final states:

- ISM: zero seniority: all particles forming $J = 0$ pairs
- EDF: only spherical contributions



Same behaviour in ISM and EDF calculations

NME scale set by pairing content of nuclear interaction

KB3G bigger NMEs than EDF!

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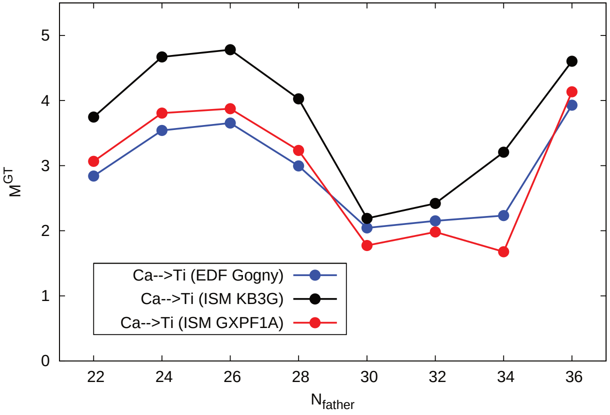

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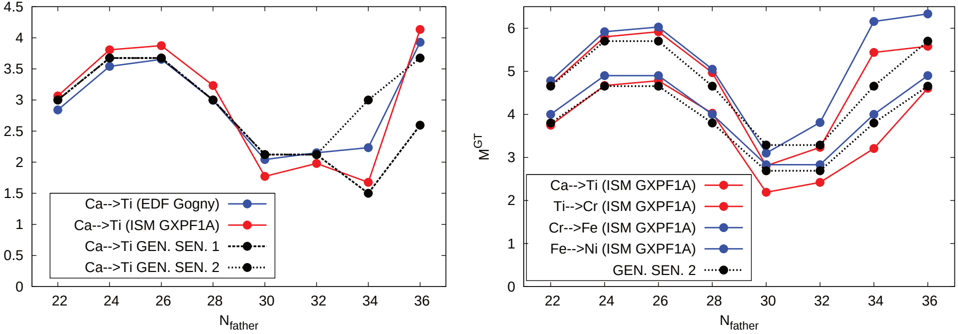
GXPF1A almost perfect agreement with EDF!

Spherical NMEs and generalized seniority model

ISM and EDF agree in $M_{GT}^{0\nu\beta\beta}$ in the spherical limit (no correlations)

Predicted by generalized seniority model Barea, Iachello PRC79 044301(2009)

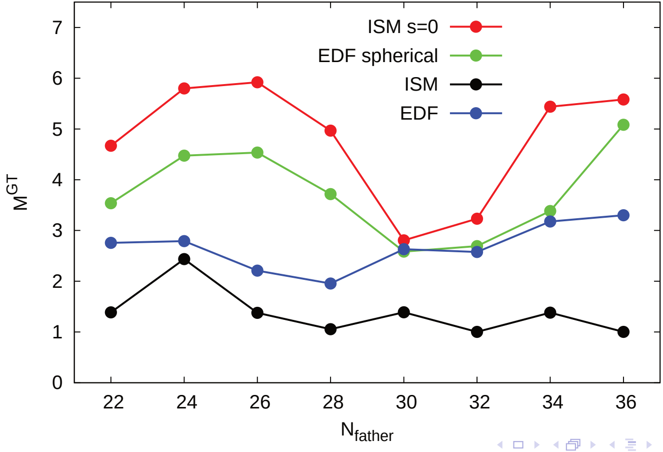
$$M_{GT}^{0\nu\beta\beta} \simeq \alpha_\pi \alpha_\nu \sqrt{N_\pi + 1}\sqrt{\Omega_\pi - N_\pi}\sqrt{N_\nu}\sqrt{\Omega_\nu - N_\nu + 1}$$



Seniority evolution of matrix elements

ISM and EDF agree in $M_{GT}^{0\nu\beta\beta}$ in the spherical limit

Difference lies in the treatment of correlations



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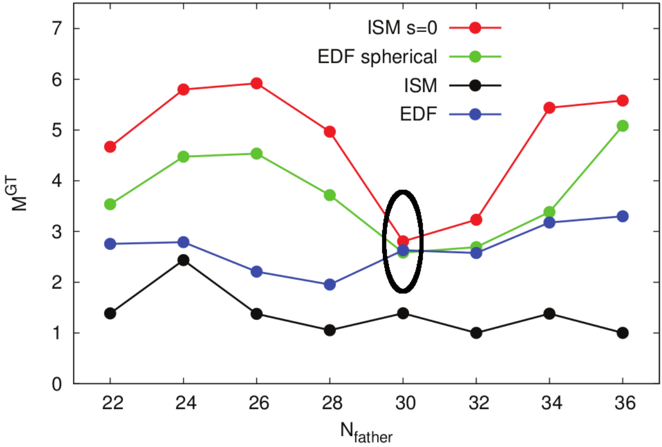
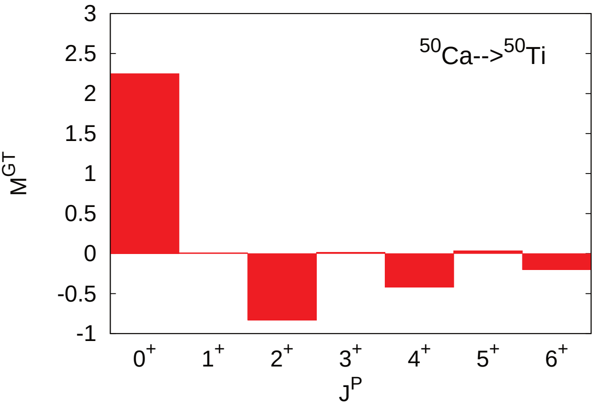
Difference lies in the treatment of correlations



$^{50}Ca \rightarrow ^{50}Ti$ (non-physical) decay

In the ISM, high seniority components in initial and (mostly) final states allow the decay of J^P pairs other than 0^+

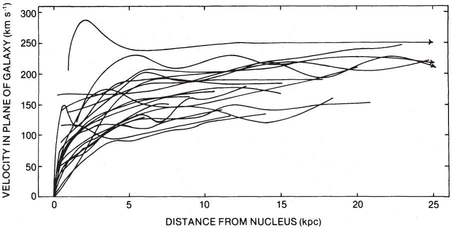
As a consequence Nuclear Matrix Elements are reduced



Outline

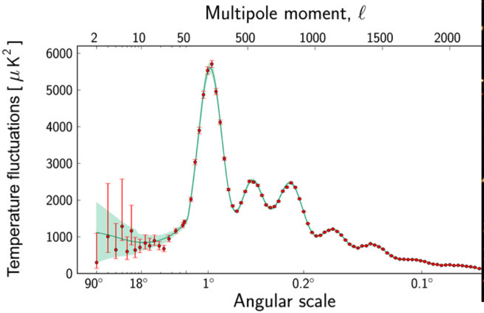
1. Neutrinoless double-beta decay
2. WIMP scattering off nuclei

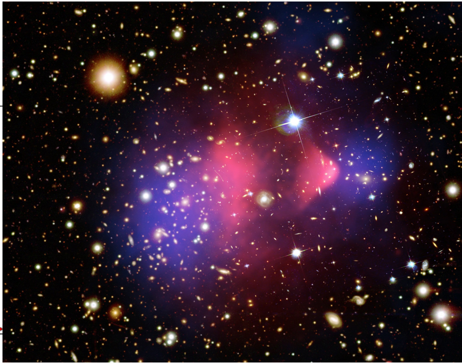
Dark Matter: evidence



Solid evidence of Dark Matter
in very different observations:

Rotation curves, Lensing, CMB...
Zwicky 1930's, Rubin 1970's,..., Planck (2013)





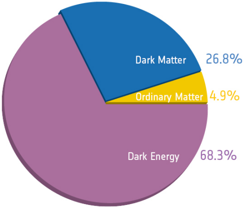
What is Dark Matter?: WIMPs

We don't know the component of Dark Matter

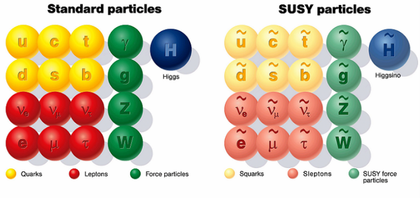
Many very different candidates have been proposed:

New particles: To be detected

- Weakly interacting massive particles (WIMPs)
- Sterile neutrinos
- Axions
- Gravitons
- . . .



Lightest supersymmetric particles (usually neutralino) predicted in SUSY extensions of the Standard Model



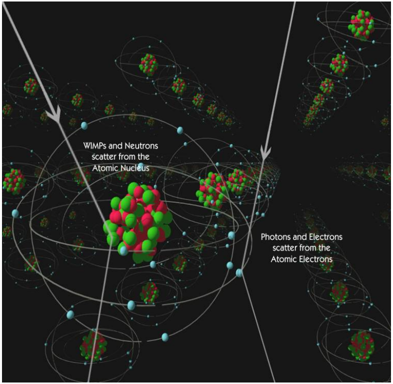
Expected WIMP-density naturally accounts for observed Dark Matter density

WIMP scattering off nuclei

We need Nuclear Matrix Elements for WIMP scattering off nuclei

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

- Nuclear structure calculation of the initial and final states: State-of-the-art Shell Model diagonalizations and interactions
- Description of the lepton-nucleus interaction: Evaluation (non-perturbative) of the hadronic currents inside nucleus



CDMS Collaboration

Spin-Independent vs Spin-Dependent

Spin-Independent interaction:

WIMPs couple to the nuclear density

Coherent sum over nucleons and protons in the nucleus

$$\sigma \propto |\langle \text{Initial} | \int dx\, j^{\mu}(x)^{SI} J_{\mu}(x)^{SI} | \text{Final} \rangle|^2 \propto |\sum_{N,Z} c_0|^2 \propto c_0^2 A^2$$

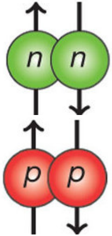
Spin-Dependent interaction:

WIMP spins couple to the nuclear spin

Pairing interaction: pairs of spins couple to $S = 0$: no coherence

Only stable nuclei with odd neutrons/protons relevant for experiment searches

Specially sensitive to nuclear structure, distribution of spin among nucleons



1b hadronic currents

At lowest orders in chiral EFT, 1-body current

$$Q^0: \quad \sum_{i=1}^{A} \mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A} \frac{1}{2}\left[a_0\sigma_i + a_1\tau_i^3\sigma_i\right],$$

$$Q^2: \quad \sum_{i=1}^{A} \mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A} \frac{1}{2}\left[a_0\sigma_i + a_1\tau_i^3\left(\frac{g_A(p^2)}{g_A}\sigma_i - \frac{g_P(p^2)}{2mg_A}(\mathbf{p}\cdot\sigma_i)\mathbf{p}\right)\right],$$

where a_0/a_1 are the isoscalar/isovector couplings

Q^2 1b currents correspond to standard phenomenological currents, slightly different p-dependence consistent with chiral EFT expansion

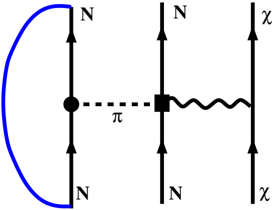
Engel et al. IJMPE1 1(1992)

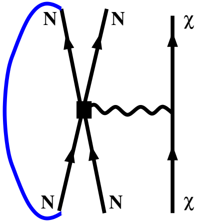
2b currents: normal-ordering

Q^3: 2b currents
Approximate in medium-mass nuclei: normal-ordered 1-body part with respect to spin/isospin symmetric Fermi gas

$$\mathbf{J}_{12}^3 = -\frac{g_A}{4F_\pi^2}\frac{1}{m_\pi^2+k^2}\Big[2\Big(c_4+\frac{1}{4m}\Big)\mathbf{k}\times(\sigma_\times\times\mathbf{k})\tau_\times^3$$
$$+4c_3\mathbf{k}\cdot(\sigma_1\tau_1^3+\sigma_2\tau_2^3)\mathbf{k}-\frac{i}{m}\mathbf{k}\cdot(\sigma_1-\sigma_2)\mathbf{q}\tau_\times^3\Big]$$

Sum over one nucleon, direct and the exchange terms





$\Rightarrow \mathbf{J}_{n,2b}^{\text{eff}}$, normal-ordered (effective) one-body current

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

Normal-ordered 2b currents

The leading (long-range) normal-ordered two-body currents are

$$\mathbf{J}_{i,2b}^{\text{eff}} = -g_A \frac{\tau_i^3}{2} \frac{\rho}{F_\pi^2} I(\rho, P=0) \left(\frac{1}{3}(2c_4 - c_3) + \frac{1}{6m} \right) \sigma_i = -g_A \frac{\tau_i^3}{2} \delta a_1 \sigma_i$$

$$\mathbf{J}_{i,2b}^{\text{eff}, P} = -g_A \frac{\tau_i^3}{2} \frac{\rho}{F_\pi^2} 2c_3 \frac{1}{4m_\pi^2 + p^2} (\mathbf{p} \cdot \sigma_i)\mathbf{p} = -g_A \frac{\tau_i^3}{2} \frac{\delta a_1^P(p^2)}{p^2} (\mathbf{p} \cdot \sigma_i)\mathbf{p}$$

Low-energy couplings c_i from nuclear forces

Range of nuclear densities $\rho = 0.10 \ldots 0.12$ fm^{-3}

	c_3	c_4	δa_1	$\delta a_1^P(p = m_\pi)$
EM	-3.2	5.4	$-(0.25...0.32)$	0.12...0.14
EM+δc_i	-2.2	4.4	$-(0.20...0.25)$	0.08...0.10
EGM	-3.4	3.4	$-(0.19...0.23)$	0.12...0.15
EGM+δc_i	-2.4	2.4	$-(0.13...0.17)$	0.09...0.10
PWA	-4.78	3.96	$-(0.23...0.29)$	0.17...0.21
PWA+δc_i	-3.78	2.96	$-(0.18...0.22)$	0.14...0.16

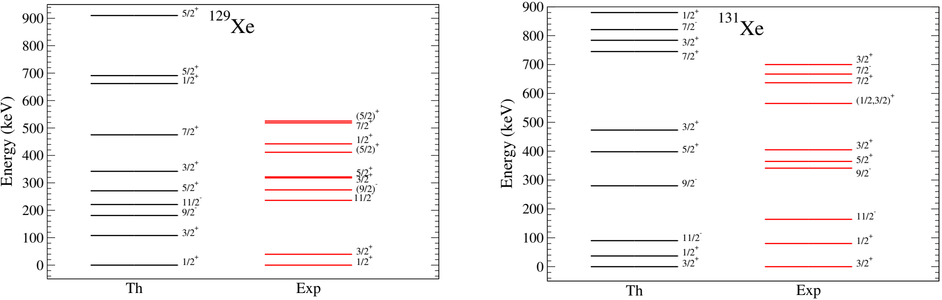
2b currents: renormalization of the isovector couplings
axial (reduction) and pseudoscalar (enhancement)

Nuclear Structure calculations

- Nuclear interactions based on NN interactions
  + many-body perturbation theory + phenomenological modifications
  (to compensate for absence of 3N forces)
- The valence spaces and interactions used are the following
  - $0g_{7/2}$, $1d_{3/2}$, $1d_{5/2}$, $2s_{1/2}$ and $0h_{11/2}$ space
    for ^{127}I, ^{129}Xe and ^{131}Xe
    gcn.5082 interaction
  - $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$ space for ^{73}Ge
    gcn.2850, rg interactions
  - *sd* shell for ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si
    usdb interaction
- These valence spaces and interactions have been tested
  in nuclear structure, β and $\beta\beta$ decay studies

^{129,131}Xe spectra

The agreement with experimental spectra is very good!



JM, Gazit, Schwenk PRD86 103511(2012)

Ordering and grouping of states well reproduced

Spin-dependent WIMP-nucleus scattering

Spin-Dependent WIMP-nucleus scattering $\Rightarrow$ odd-A nuclei

The interaction Hamiltonian has a leptonic current (neutralino) and a hadronic current (nucleons in the nucleus)

$$\langle f|\mathcal{L}_\chi^{SD}|i\rangle = -\frac{G_F}{\sqrt{2}}\int d^3\mathbf{r}\,\mathbf{j}_{fi}(\mathbf{r})\,\mathbf{J}_{fi}^A(\mathbf{r}) = -\frac{G_F}{\sqrt{2}}\int d^3\mathbf{r}\,e^{-i\mathbf{p}\cdot\mathbf{r}}\,\bar{\chi}\gamma\gamma_5\chi\,\mathbf{J}_{fi}^A(\mathbf{r})$$

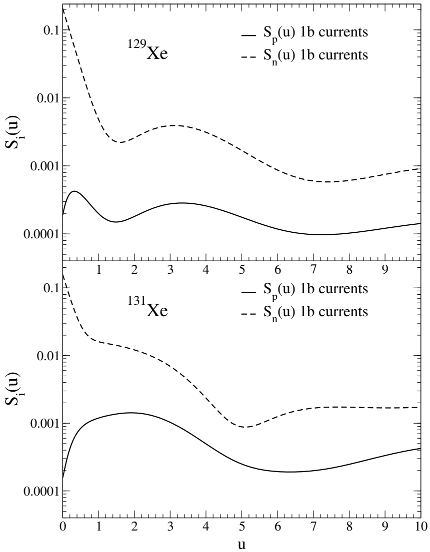
Assuming non-relativistic ($v/c \sim 10^{-3}$) WIMPs with spin $1/2$ the scattering cross-section is related to the Structure Factor S(p)

$$\frac{\mathbf{d}\sigma}{\mathbf{dp}} \propto \frac{1}{2}\sum_{s_i,s_f}\frac{1}{2J_i+1}\sum_{M_i,M_f}|\langle f|\mathcal{L}_\chi^{SD}|i\rangle|^2 = G_F^2\frac{4\pi}{2J_i+1}\mathbf{S_A}(\mathbf{p})$$

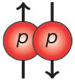
$$\mathbf{S_A}(\mathbf{p}) = \sum_L\left(\left|\langle J_f||\mathcal{T}_L(p)||J_i\rangle\right|^2 + \left|\langle J_f||\mathcal{M}_L(p)||J_i\rangle\right|^2 + \left|\langle J_f||\mathcal{L}_L(p)||J_i\rangle\right|^2\right)$$

Multipoles: Trans. Electric Trans. Magnetic Longitudinal

Structure Factors with 1b currents



In $^{129,131}_{54}$Xe $\langle S_n \rangle \gg \langle S_p \rangle$,



$S_p = \sum_{i=1}^{Z} \sigma_i/2$, $S_n = \sum_{i=1}^{N} \sigma_i/2$

At $p = 0$ "Neutron"/"Proton" couplings maximize/minimize S_A:

$$S_A = \frac{(2J+1)(J+1)}{\pi J} \left| a_p \langle S_p \rangle + a_n \langle S_n \rangle \right|^2,$$

$$a_{n/p} = (a_0 \mp a_1)/2,$$

$$S_n(0) \propto \left| \langle S_n \rangle \right|^2 \; S_p(0) \propto \left| \langle S_p \rangle \right|^2.$$

JM, Gazit, Schwenk PRD86 103511(2012)

Klos, JM, Gazit, Schwenk, arXiv:1304.7684

1b+2b currents: multipole decomposition

The multipoles, with the contributions from 1b+2b currents are

$$\mathcal{T}_L(p) = \frac{1}{\sqrt{2L+1}} \sum_{i=1}^{A} \frac{1}{2} \left[a_0 + a_1 \tau_i^3 \left(1 - 2\frac{p^2}{\Lambda_A^2} + \delta a_1 \right) \right] \times \left[-\sqrt{L} M_{L,L+1}(p\mathbf{r}_i) + \sqrt{L+1} M_{L,L-1}(p\mathbf{r}_i) \right]$$

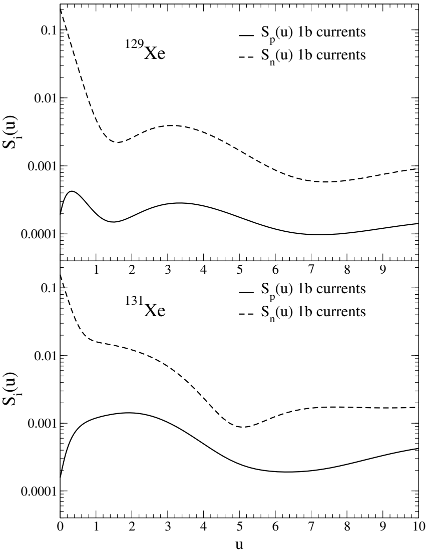
$$\mathcal{L}_L(p) = \frac{1}{\sqrt{2L+1}} \sum_{i=1}^{A} \frac{1}{2} \left[a_0 + a_1 \tau_i^3 \left(1 + \delta a_1 - \frac{2 g_{\pi pn} F_\pi \, p^2}{2 m g_A (m_\pi^2 + p^2)} + \delta a_1^P(p) \right) \right] \times \left[\sqrt{L+1}\, M_{L,L+1}(p\mathbf{r}_i) + \sqrt{L} M_{L,L-1}(p\mathbf{r}_i) \right],$$

$$\mathcal{M}_L(p) = \sum_{i=1}^{A} \frac{1}{2} \left[a_0 + a_1 \tau_i^3 \left(1 - 2\frac{p^2}{\Lambda_A^2} + \delta a_1 \right) \right] M_{L,L}(p\mathbf{r}_i), \text{with } M_{L,L'}(p\mathbf{r}_i) = j_{L'}(p r_i) [Y_{L'}(\hat{\mathbf{r}}_i)\, \sigma_i]^L.$$

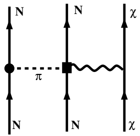
⇒ Reduction in the isovector response due to δa_1: all multipoles

⇒ At large p values, enhancement due to δa_1^P: $\mathcal{L}_L(p)$

⇒ Overall response depends on relative $\mathcal{L}_L(p)$ vs $\mathcal{T}_L(p)$ contributions



2b currents naturally involve neutrons and protons at the same time:



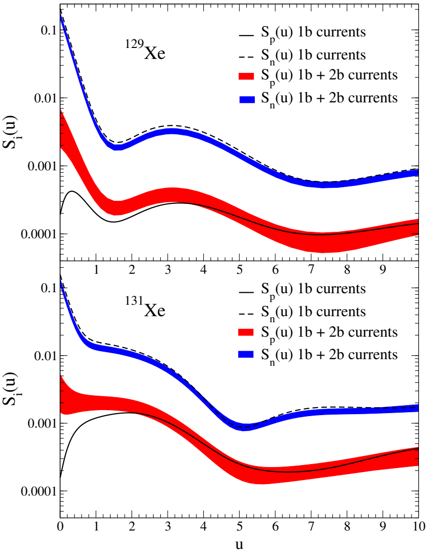
In the $a_1 = a_0$ “proton” case, neutrons contribute through 2b currents, at all p

$S(0) \propto$

$$\left| \frac{a_0 + a_1(1+\delta a_1)}{2} \langle S_p \rangle + \frac{a_0 - a_1(1+\delta a_1)}{2} \langle S_n \rangle \right|^2,$$

$\langle S_n \rangle \gg \langle S_p \rangle$, dramatic increase in $S_p(u)$

Structure Factor, “neutron” and “proton”, dominated by the odd species



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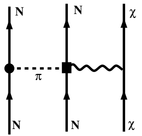

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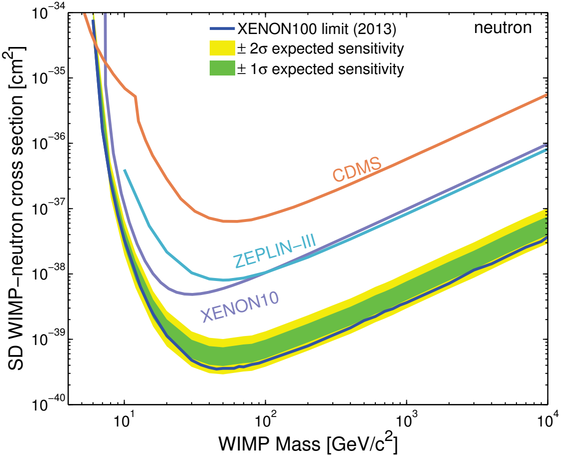
$$S(0) \propto \left| \frac{a_0 + a_1(1+\delta a_1)}{2} \langle S_p \rangle + \frac{a_0 - a_1(1+\delta a_1)}{2} \langle S_n \rangle \right|^2,$$

$\langle S_n \rangle \gg \langle S_p \rangle$, dramatic increase in $S_p(u)$

Structure Factor, “neutron” and “proton”, dominated by the odd species

Application to experiment: XENON100

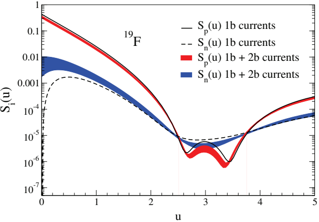


Our calculations used by XENON100 Collaboration to set limits on WIMP-nucleus cross-sections (σ)

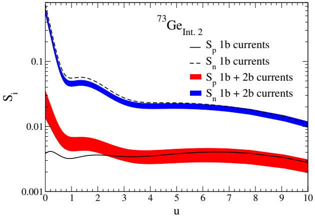
XENON100 obtained world best limits (σ above limit excluded) for Spin-Dependent scattering with “neutron” couplings

Aprile et al. PRL111 021301 (2013)

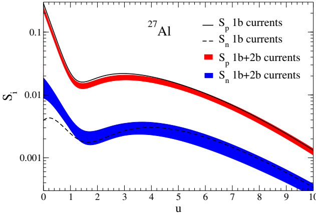
$^{19}_{9}$F, $^{23}_{11}$Na, $^{27}_{13}$Al, $^{29}_{14}$Si, $^{73}_{32}$Ge, $^{127}_{53}$I



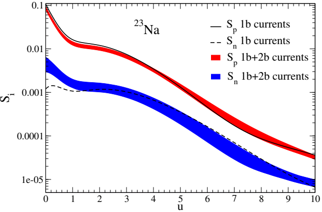
PICASSO, COUPP, SIMPLE



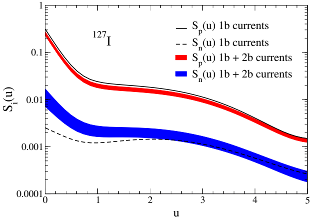
CDMS, EDELWEISS, EURECA



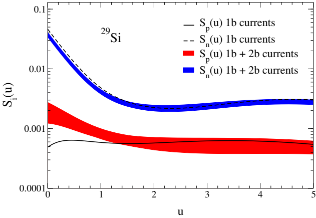
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



CDMS-II

Summary and Outlook

Nuclear Matrix Elements key for experiments on Fundamental Symmetries

Chiral EFT hadronic currents: 2b currents correct standard operators

State-of-the-art nuclear ISM structure calculations: good spectroscopy

Matrix Elements for Neutrinoless $\beta\beta$ decay

- 2b currents reduce (quench) Matrix Elements in $15\% - 40\%$
- *p*-dependence of GT reduction predicted ($0\nu\beta\beta$ less quenched than GT)
- Benchmark of ISM and EDF NMEs at spherical/seniority zero limit

Structure Factors for Spin-Dependent elastic WIMP scattering off nuclei

- Reduce the isovector dominant Structure Factor
- Strong increase in sub-dominant Structure Factor at low *p*

Outlook

- Consistent calculations based on chiral EFT forces and currents
- Better understand correlations in $0\nu\beta\beta$ decay NMEs