From atomic nuclei to neutrinos and dark matter

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Outline

1. Nuclear structure with chiral effective field theory
2. Matrix elements for $\beta\beta$ decay
3. Dark matter scattering off nuclei

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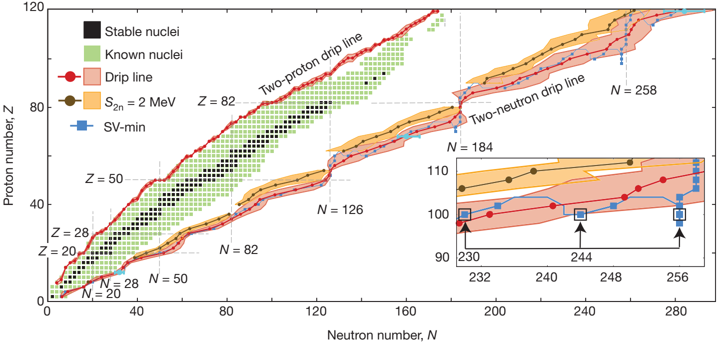
1. Nuclear structure with chiral effective field theory

2. Matrix elements for $\beta\beta$ decay

3. Dark matter scattering off nuclei

Nuclear landscape

The goal of nuclear physics is a unified description of nuclear structure, across the nuclear chart and based on nuclear forces



∼ 3000 isotopes measured

∼ 7000 predicted

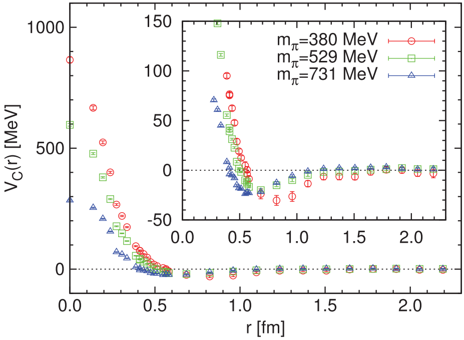
Erler et al.
Nature 486 509 (2012)

Limits of existence, ground-state properties, shell evolution, excitation spectra, spectroscopy, shape coexistence, β decays, fission...

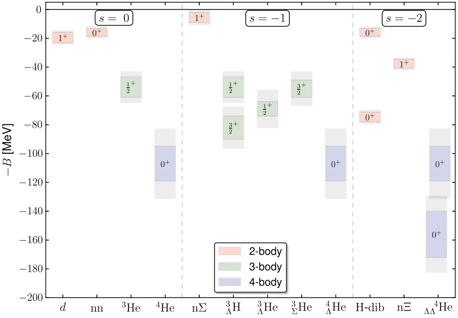
Connect to underlying theory of strong interactions: QCD

QCD non-perturbative at low energies relevant for nuclear structure

Lattice QCD solves the QCD Lagrangian in discretized space-time Lattice



HALQCD Collaboration



NPLQCD Collaboration

Nuclear potentials, and lightest nuclei and hypernuclei solved at non-physical pion mass $m_\pi \sim 400 - 800$ MeV, ongoing improvements

Effective theory for nuclear structure

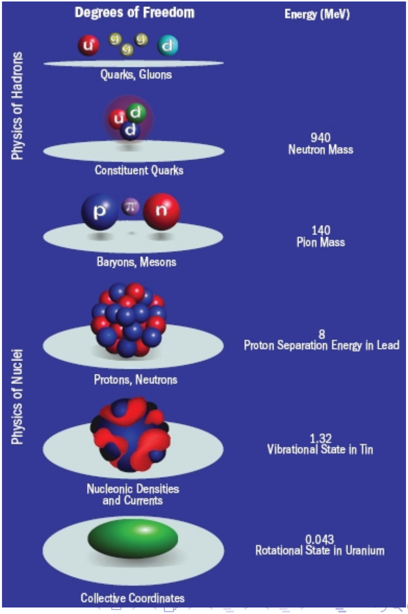
Effective theory:
approximation of the full theory
valid at relevant scales

Exploit chiral symmetry:
pions, protons and neutrons
degrees of freedom of the theory

Expansion in terms of small parameter:
typical scale $\sim m_\pi$ / breakdown scale Λ

Physics resolved at relevant energies
explicit (pion-exchanges)

Unresolved physics
encoded in contact terms
(Low Energy Couplings)

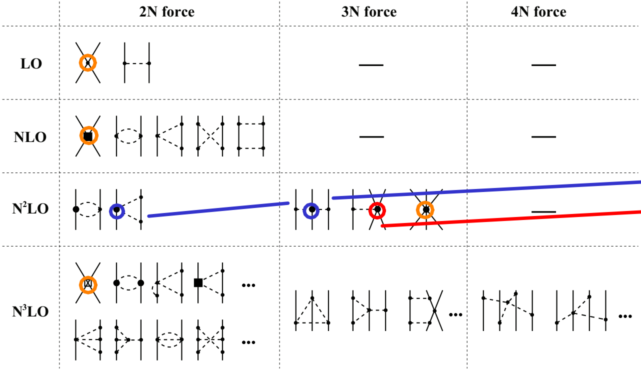


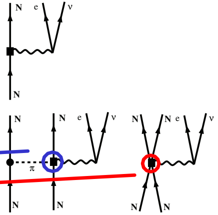
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





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

Park, Gazit, Klos, Baroni...

Short-range couplings fitted to experiment once

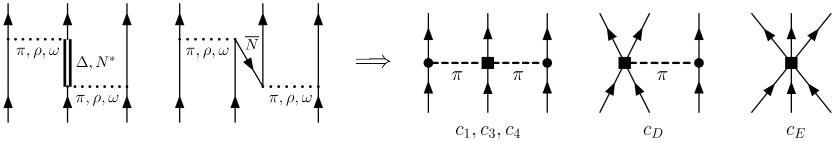
Three-nucleon forces

3N forces known for a long time (also 2b currents)

Fujita and Miyazawa PTP17 (1957), Towner Phys. Rep. 155 (1987)...

3N forces originate in the elimination of degrees of freedom
(N-body forces appear in any effective theory)

Bogner, Schwenk, Furnstahl PPNP65 94 (2010)



Difficult to constrain directly

$\Rightarrow$ Chiral EFT, in a natural and systematic manner,
treats 3N forces consistent with NN forces (same for 2b and 1b currents)

3N forces can explain the great success of the phenomenological shell model

Brown, Caurier, Nowacki, Otsuka, Poves, Zuker

Oxygen dripline in ab-initio calculations

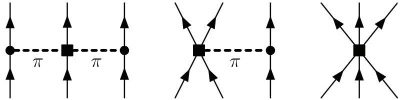
Oxygen dripline including chiral NN+3N forces correctly reproduced confirmed in ab-initio calculations by different approaches, treating explicitly all nucleons as degrees of freedom

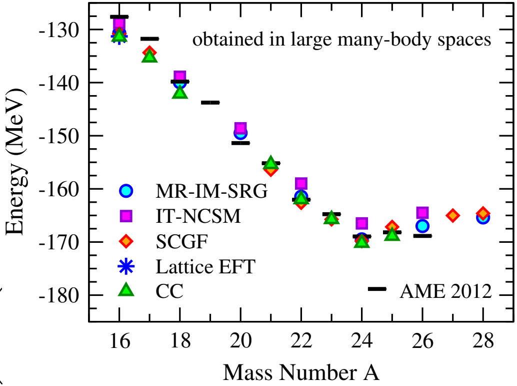
No-core shell model (Importance-truncated)

In-medium SRG
Hergert et al. PRL110 242501 (2013)

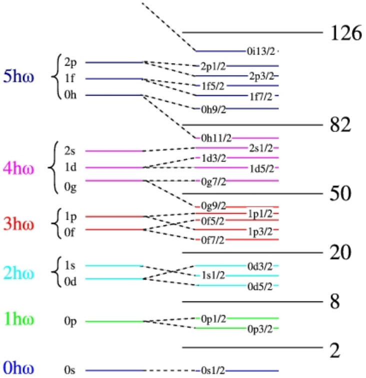
Self-consistent Green's function
Cipollone et al. PRL111 062501 (2013)

Coupled-cluster
Jansen et al. PRL113 142502 (2014)





Nuclear shell model



Nuclear shell model configuration space only keep essential degrees of freedom

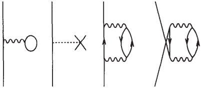
- Outer orbits: always empty
- Valence space: where many-body problem is solved
- Inner core: always filled

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

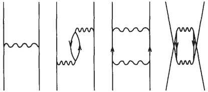
$$|\Psi\rangle_{eff} = \sum_{\alpha} c_{\alpha}\,|\phi_{\alpha}\rangle\,, \quad |\phi_{\alpha}\rangle = a^{+}_{i1} a^{+}_{i2} \ldots a^{+}_{iA}\,|0\rangle$$

Many-body perturbation theory to generate H_{eff}

Single Particle Energies



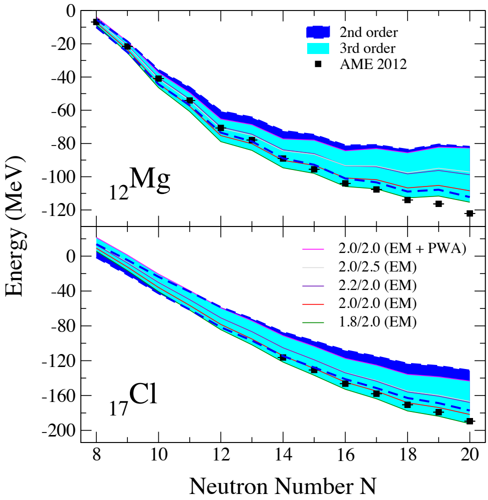
Two-Body Matrix Elements



Shell model codes diagonalize up to $\sim 10^{10}$ Slater det's Caurier *et al.* RMP 77 (2005)

Medium-mass nuclei and theoretical uncertainties

The shell model permits to extend the study to medium-mass (*sd*-shell) nuclei



Simonis, Hebeler, Holt, JM, Schwenk
PRC93 011302 (2016)

Explore the theoretical sensitivity:

Initial chiral Hamiltonian

RG evolution of NN, 3N forces

Convergence in MBPT

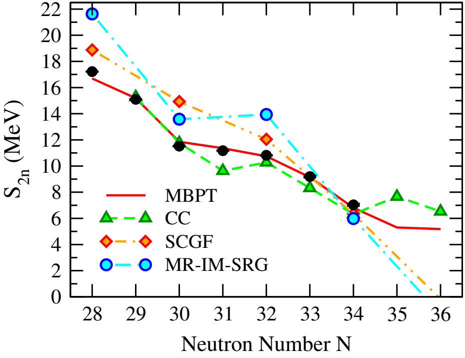
Use Hamiltonians with good nuclear saturation properties
Hebeler et al. PRC 83 031301 (2011)

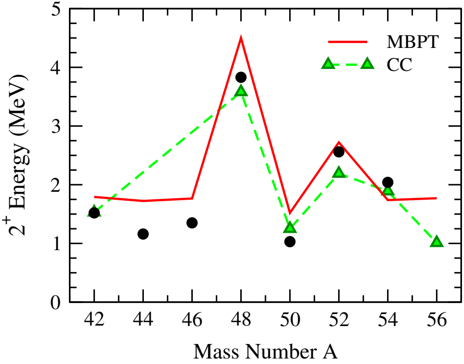
Magnesium ground-state energies underbound, Chlorine good agreement to experiment

Uncertainties dominated by initial nuclear Hamiltonian

Calcium isotopes with NN+3N forces

Calculations with NN+3N forces predict shell closures at ^{52}Ca, ^{54}Ca



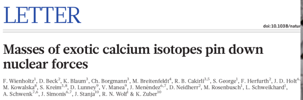


$^{51-54}$Ca masses [TRIUMF/ISOLDE]

^{54}Ca 2_1^+ state excitation energy [RIBF]

Hebeler, Holt, JM, Schwenk ARNPS 65 457(2015)

Similar agreement with phenomenological interactions



LETTER

doi:10.1038/natur

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

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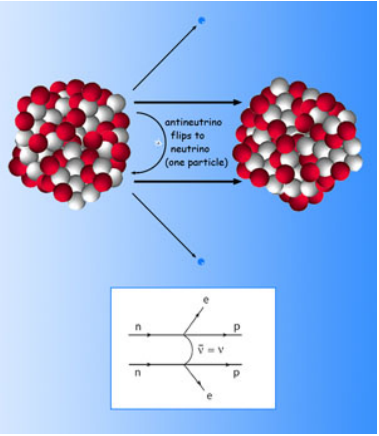
1 Nuclear structure with chiral effective field theory

2 Matrix elements for $\beta\beta$ decay

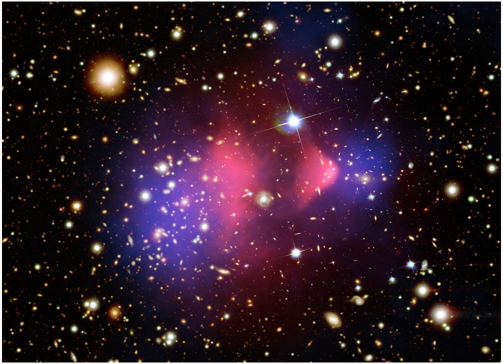
3 Dark matter scattering off nuclei

Neutrinoless $\beta\beta$ decay, dark matter detection



Neutrinoless double-beta decay

Lepton number violation
Majorana / Dirac nature of neutrinos
Neutrino masses and hierarchy



Dark matter scattering off nuclei

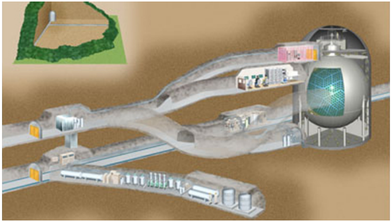
What is dark matter made of?

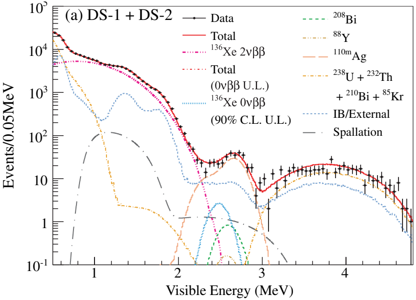
Neutrinos, Dark Matter can be studied with high-energy experiments

Nuclear physics offers an alternative:
Nuclei are abundant in huge numbers $N_A = 6.02\ 10^{23}$ nuclei in A grams!

Lots of material over long times provides access to detect
very rare decays and very small cross-sections!

Isolate from other processes:
very low background (underground)





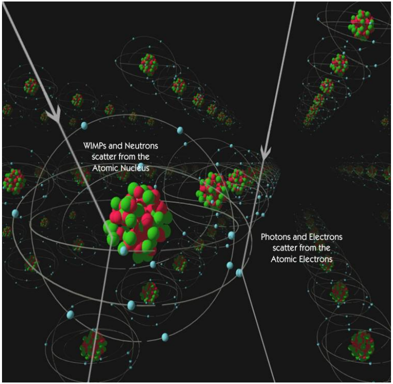
KamLAND-Zen

Nuclear matrix elements

Nuclear matrix elements are needed to study fundamental symmetries

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

- Nuclear structure calculation of the initial and final states: Ab initio, shell model, energy density functional...
- Lepton-nucleus interaction: Evaluate (non-perturbative) hadronic currents inside nucleus: phenomenology, effective theory

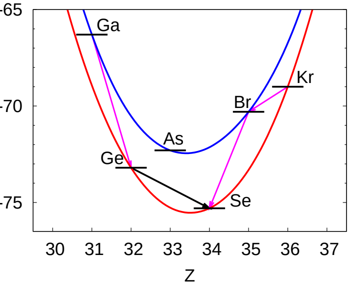


CDMS Collaboration

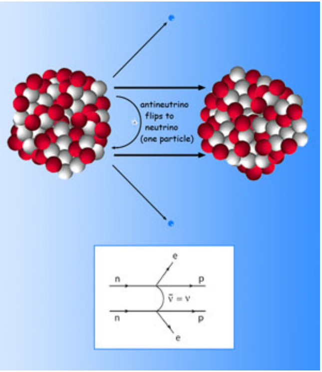
Neutrinoless double-beta decay

Lepton-number violation, Majorana nature of neutrinos

Second order process only observable if single-β-decay is energetically forbidden or hindered by large ΔJ



^{48}Ca $\rightarrow$ ^{48}Ti
^{76}Ge $\rightarrow$ ^{76}Se
^{82}Se $\rightarrow$ ^{82}Kr
^{96}Zr $\rightarrow$ ^{96}Mo
^{100}Mo $\rightarrow$ ^{100}Ru
^{110}Pd $\rightarrow$ ^{110}Cd
^{116}Cd $\rightarrow$ ^{116}Sn
^{124}Sn $\rightarrow$ ^{124}Te
^{130}Te $\rightarrow$ ^{130}Xe
^{136}Xe $\rightarrow$ ^{136}Ba
^{150}Nd $\rightarrow$ ^{150}Sm

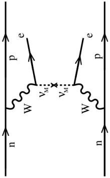


Lifetime limits: ^{76}Ge (GERDA), ^{136}Xe (EXO, KamLAND) $T^{0\nu\beta\beta}_{1/2} > 10^{25}$ y!

$0\nu\beta\beta$ 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

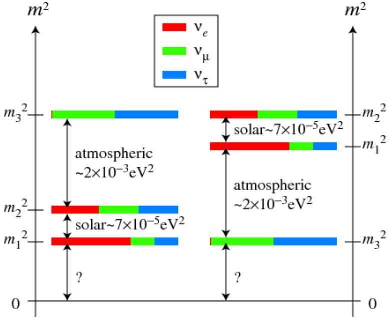
η_i describes Beyond Standard Model physics

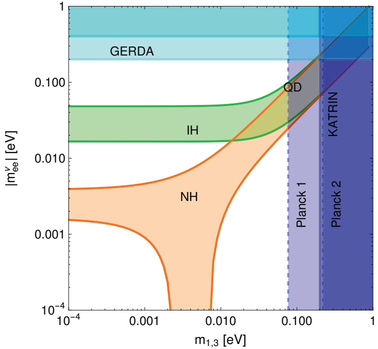
Exchange of Standard Model neutrinos, sterile neutrinos ($\eta \sim m_\nu$),
right-handed currents ($\eta \sim$ mass of exchange boson W_R, mixing to W_L),
exchange of supersymmetric particles ($\eta \sim$ LNV couplings)

Exchange of Standard Model neutrinos

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

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





Compete with single-β decay $\left(\sqrt{\sum |U_{ek}|^2 m_k^2}\right)$ and cosmology $\left(\sum m_k\right)$

Neutrinoless $\beta\beta$ decay operator

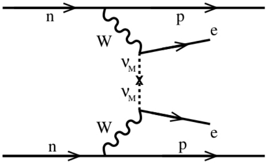
The matrix element is $$M^{0\nu\beta\beta} = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\, \Omega^X \, |0_i^+\rangle$$

- $\tau_n^- \tau_m^-$ 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

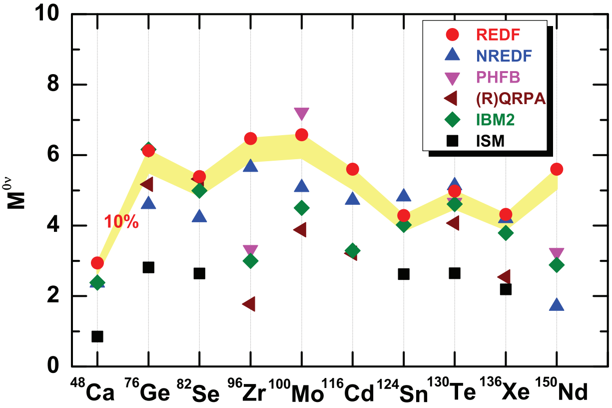
$$H^X(r) = \frac{2}{\pi}\frac{R}{g_A^2(0)}\int_0^\infty f^X(pr)\frac{h^X(p^2)}{\left(\sqrt{p^2+m_\nu^2}\right)\left(\sqrt{p^2+m_\nu^2}+\langle E^m\rangle - \frac{1}{2}(E_i-E_f)\right)}p^2\,dp \sim \frac{R}{r}$$

$2\nu\beta\beta$ 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 matrix element calculations, same transition operator



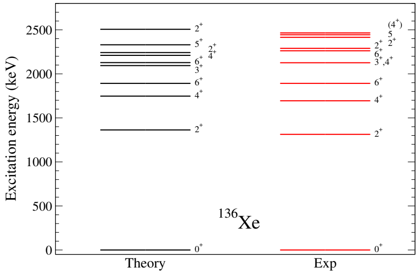
Yao et al. PRC91 024316 (2015)

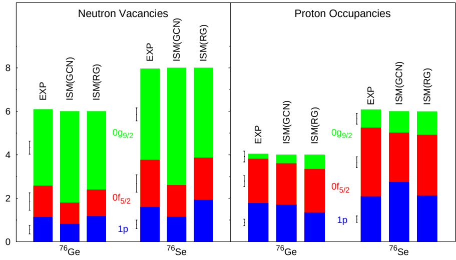
EDF, IBM, QRPA large matrix elements: How well they include nuclear structure correlations?

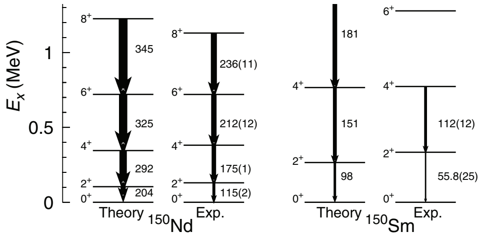
Shell model small matrix elements: What is the effect of the small valence space?

Test of nuclear structure

Nuclear spectroscopy well reproduced by (phenomenological) calculations: masses, excitation energies, transitions, knockout reactions...







Shell model calculation:

JM, Caurier, Nowacki, Poves

PRC80 048501 (2009)

EDF calculation:

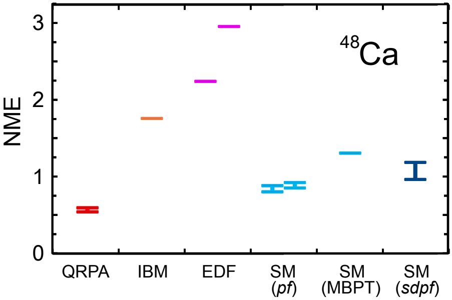
Rodríguez, Martínez-Pinedo

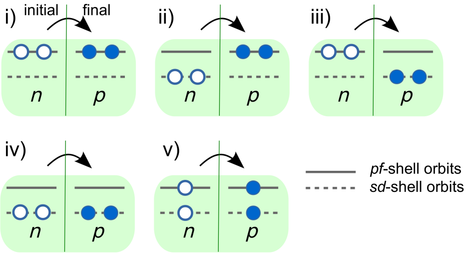
PRL105 252503 (2010)

Shell model configuration space

For ^{48}Ca, enlarging the configuration space from *sd* to *sdpf* (4 to 7 orbitals) increases matrix elements only moderately 30%

Iwata et al. PRL accepted



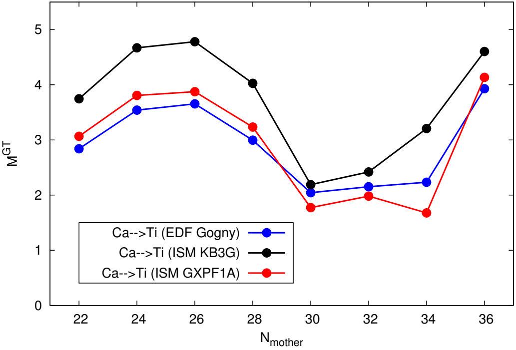


The contributions dominated by pairing (2h-2h) excitations enhance the $\beta\beta$ matrix element,
but the contributions dominated by 1p-1h excitations suppress the $\beta\beta$ matrix element

$0\nu\beta\beta$ 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

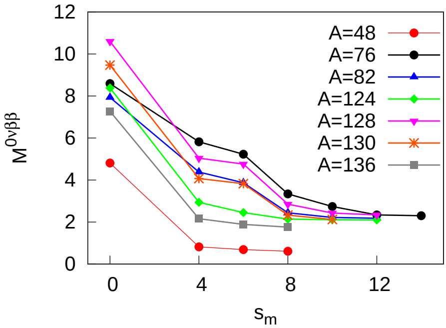
JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)

NME follows generalized seniority model:

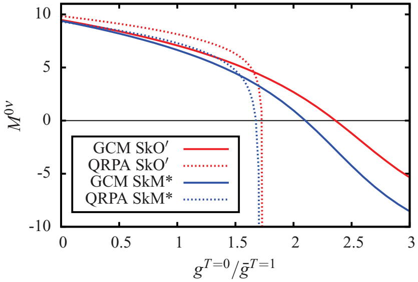
$$M_{GT}^{0\nu\beta\beta} \simeq \alpha_\pi \alpha_\nu \sqrt{N_\pi + 1}\sqrt{\Omega_\pi - N_\pi}\sqrt{N_\nu}\sqrt{\Omega_\nu - N_\nu + 1},$$ Barea, Iachello PRC79 044301(2009)

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

$0\nu\beta\beta$ decay very sensitive to pairing
Matrix elements too large if too many proton-proton, nucleon-nucleon pairs or if proton-neutron correlations are neglected



Caurier et al. PRL100 052503 (2008)



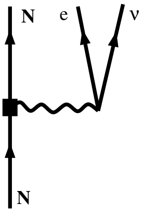
Hinohara, Engel PRC90 031301 (2014)

Approximate SU(4) symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator, $\Rightarrow M^{GT} \sim 0$
Mixing of irreps in mother, daughter due to $H(r)$, nuclear interaction

Weak transitions in nuclei: quenching

β and $\beta\beta$ decay processes driven by Weak interaction

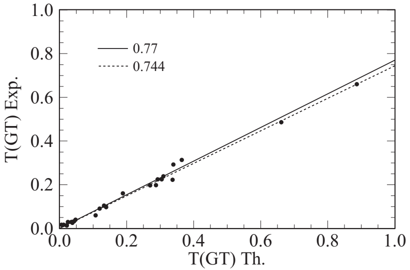
$$\mathcal{L}_W = \frac{G_F}{\sqrt{2}} \left(j_{L\mu} J_L^{\mu\dagger} \right) + H.c.$$



$j_{L\mu}$ leptonic current (electron, neutrino)

$J_L^{\mu\dagger}$ hadronic current (nucleons)

Single-β, $2\nu\beta\beta$ decays well described by nuclear structure: shell model...



For agreement theory needs to "quench" Gamow-Teller operator

$$\langle F | \sum_i g_A^{\text{eff}} \boldsymbol{\sigma}_i \tau_i^- | I \rangle , \quad g_A^{\text{eff}} \approx 0.7 g_A$$

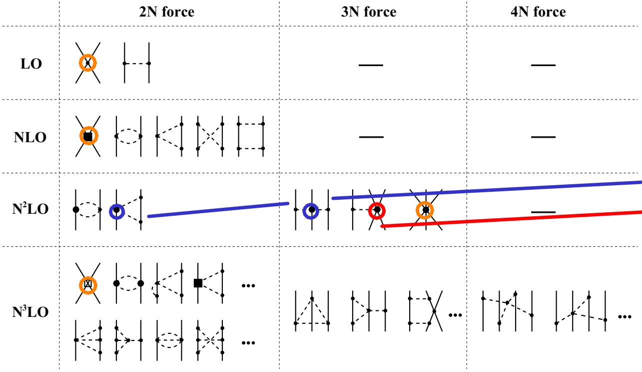
Martinez-Pinedo et al. PRC53 2602(1996)

Chiral Effective Field Theory

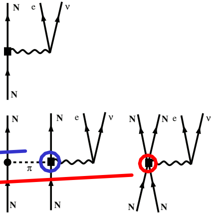
Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



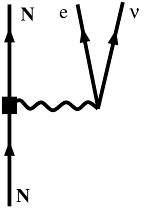
Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...



Park, Gazit, Klos, Baroni...

Short-range couplings fitted to experiment once

Hadronic weak currents in chiral EFT



At lowest orders Q^0, Q^2 1b currents only

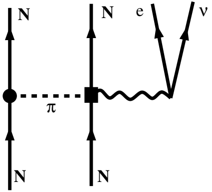
$$J_i^0(p) = g_V(p^2)\tau^-,$$

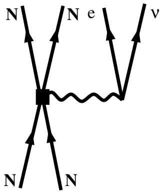
$$\boldsymbol{J}_i(p) = \left[g_A(p^2)\boldsymbol{\sigma} - g_P(p^2)\frac{(\boldsymbol{p}\cdot\boldsymbol{\sigma}_i)\boldsymbol{p}}{2m} + i\,(g_M + g_V)\,\frac{\boldsymbol{\sigma}_i \times \boldsymbol{p}}{2m}\right]\tau^-,$$

At order Q^3 chiral EFT
2b currents predicted

Reflect interactions
between nucleons in nuclei

Long-range currents dominate





$$\mathbf{J}_{12}^3 = -\frac{g_A}{4F_\pi^2}\frac{1}{m_\pi^2 + k^2}\left[2c_4\mathbf{k}\times(\boldsymbol{\sigma}_\times \times \mathbf{k})\tau_\times^3 + 4c_3\mathbf{k}\cdot\left(\boldsymbol{\sigma}_1\tau_1^3 + \boldsymbol{\sigma}_2\tau_2^3\right)\mathbf{k}\right]$$

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

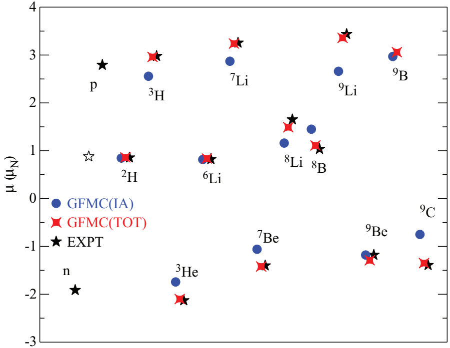
^{8}Be EM transitions

Pastore et al. PRC87 035503(2013)

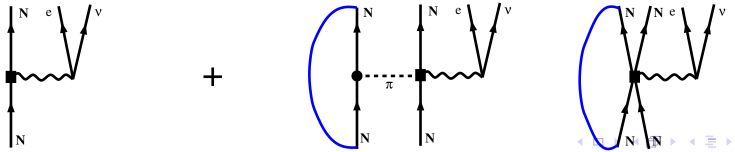
Pastore et al. PRC90 024321(2014)

^{3}H μ capture

Marcucci et al. PRC83 014002(2011)



In medium-mass nuclei, chiral EFT 1b + 2b currents (normal ordering)

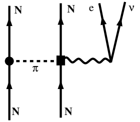


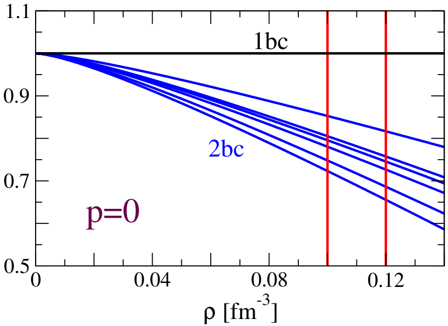
2b currents in medium-mass nuclei

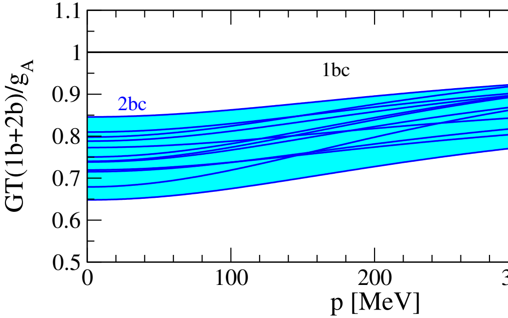
Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

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



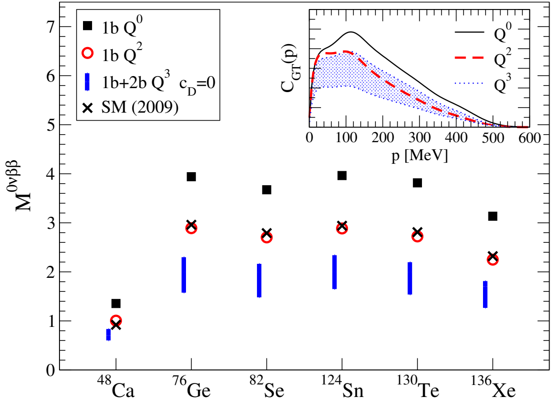




2b currents predict g_A quenching $q = 0.85...0.66$

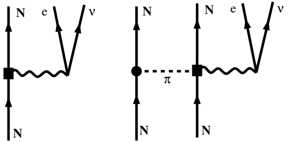
Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$

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)



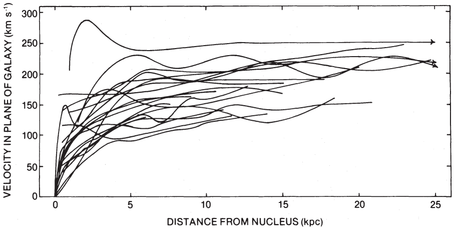
Order Q^3 2b currents reduce NMEs $\sim$ 15% $-$ 40%

Smaller quenching $q = 0.96...0.92$ Ekström et al. PRL113 262504 (2014)
Coupled-Cluster calculations of lighter ^{14}C, ^{22}O and ^{24}O
2b currents normal-ordered with respect to Hartree-Fock state

Outline

1. Nuclear structure with chiral effective field theory
2. Matrix elements for $\beta\beta$ decay
3. Dark matter scattering off nuclei

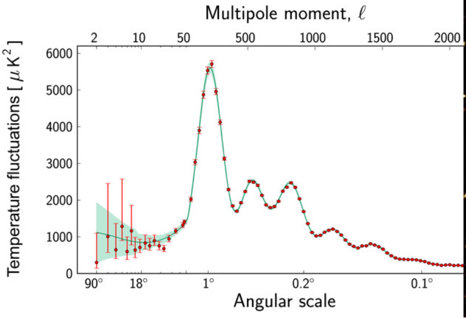
Dark matter: evidence

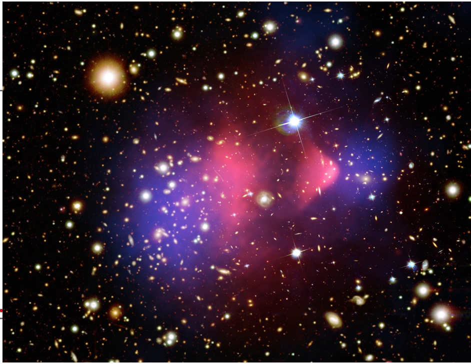


Solid evidence of dark matter
in very different observations:

Rotation curves, Lensing, CMB...

Zwicky 1930's, Rubin 1970's..., Planck 2010's

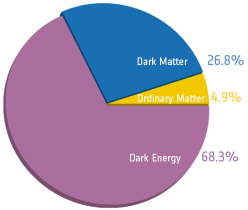




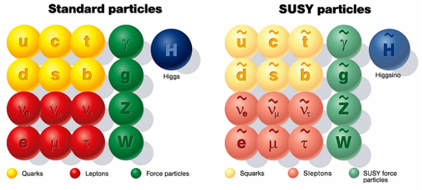
What is dark matter made of?

The composition of dark matter is unknown
High-energy physics: candidates proposed beyond Standard Model

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

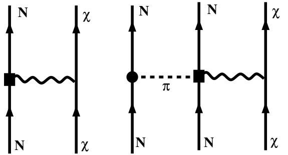


Lightest supersymmetric particles (usually neutralinos) predicted in SUSY extensions of the Standard Model



Expected WIMP-density agrees with observed dark matter density

WIMP scattering off nuclei



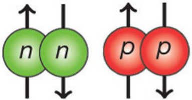
The challenge is direct dark matter detection

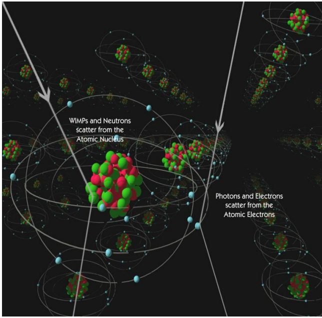
WIMPs interact with quarks $\Rightarrow$ nuclei

Direct detection experiments: XENON100, LUX
nuclear recoil from WIMP scattering off nuclei
sensitive to dark matter masses $\gtrsim$ 1 GeV

WIMPs couple to the nuclear density

For elastic scattering, coherent sum
over nucleons and protons in the nucleus





CDMS Collaboration

WIMP spins couple to the nuclear spin

Pairing interaction: Two spins couple to $S = 0$
Only relevant in stable odd-mass nuclei

WIMP-nucleon interactions

The leading-order WIMP-nucleus interaction predicted by chiral EFT is

Coupling to nuclear density: scalar-scalar (spin-independent)
Coupling to the spin: axial-axial (spin-dependent)

$$\mathcal{L}_\chi^{\mathrm{SI}} + \mathcal{L}_\chi^{\mathrm{SD}} = \frac{G_F}{\sqrt{2}} \int d^3\mathbf{r} \, \left[j(\mathbf{r}) S(\mathbf{r}) + j^\mu(\mathbf{r}) J_\mu^A(\mathbf{r}) \right]$$

$j(\mathbf{r}) = \bar{\chi}\chi = \delta_{s_f\, s_i} e^{-i\mathbf{qr}}$ leptonic (WIMP) scalar current
$S(\mathbf{r}) = c_0 \sum_{i=1}^A \delta^3(\mathbf{r} - \mathbf{r}_i)$ hadronic scalar current

$j^\mu(\mathbf{r}) = \overline{\chi}\gamma\gamma_5\chi \, e^{-i\mathbf{qr}}$ leptonic (WIMP) axial current
$J_\mu^A(\mathbf{r}) = \sum_{i=1}^A J_{\mu,i}^A(\mathbf{r}) \delta^3(\mathbf{r} - \mathbf{r}_i)$ hadronic axial current

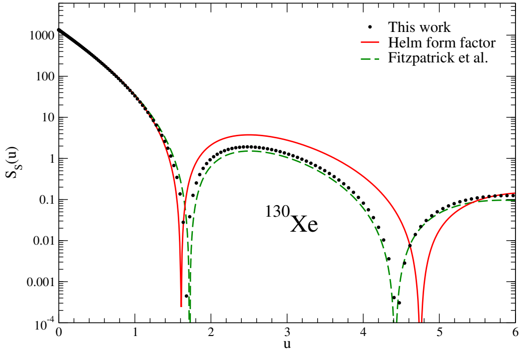
Matrix element of the dark matter scattering: structure factor

$$\frac{d\sigma}{dq^2} = \frac{8G_F^2}{(2J_i+1)v^2} S(q), \quad S(q) = \frac{1}{4\pi G_F^2} \sum_{s_f,s_i} \sum_{M_f,M_i} \left| \langle J_f M_f | \mathcal{L}_\chi^{\mathrm{SI}} + \mathcal{L}_\chi^{\mathrm{SD}} | J_i M_i \rangle \right|^2$$

Spin-independent structure factor for ^{130}Xe

Coherent response at $p = 0$, lost at finite momentum transfers

$$S_S(q) = \sum_{L=0}^{\infty} \left| \langle J_f \| c_0 \sum_{i=1}^{A} j_L(qr_i) Y_L(\mathbf{r}_i) \| J_i \rangle \right|^2 \rightarrow_{q \to 0} \frac{c_0^2}{4\pi} (2J+1) A^2 \,,$$



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

Plot as function of dimensionless $u = p^2 b^2/2$
b harmonic oscillator length

Only low-momentum transfers up to $u \sim 2$ relevant for present experiments

Not very sensitive to nuclear structure details: similar results with model constant density + gaussian surface

Outlook: which are the leading corrections? Vector-vector interactions?

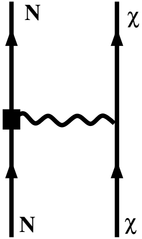
Spin-dependent hadronic currents

Calculate axial hadronic currents
Derive predicted currents within chiral EFT (similar to Weak transitions)

At lowest orders Q^0 and Q^2 in chiral EFT, 1b currents

$$Q^0: \quad \sum_{i=1}^{A} \mathbf{J}_{i,1\mathrm{b}} = \sum_{i=1}^{A} \frac{1}{2}\left[\underbrace{a_0 \boldsymbol{\sigma}_i}_{\text{isoscalar}} + \underbrace{a_1 \tau_i^3 \boldsymbol{\sigma}_i}_{\text{isovector}}\right],$$

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



Isoscalar and isovector (distinguish neutrons and protons) components

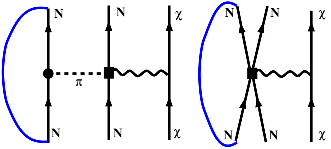
Isovector components have axial (dominant) and pseudoscalar term

Spin-dependent 2b currents

Leading Q^3 correction: 2b currents

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

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



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

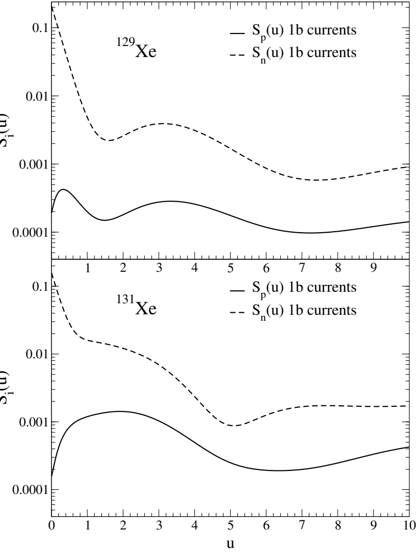
$$\mathbf{J}^{\text{eff}}_{i,2b} = \sum_{\boldsymbol{\sigma}_j}^{FG}\sum_{\tau_j}^{FG}\int\frac{p_j^2\,dp_j}{(2\pi)^3}\,\mathbf{J}_{i,j,2b}\,(1-P_{ij})$$

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

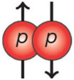
$$\mathbf{J}^{\text{eff},\,P}_{i,2\text{b}} = -g_A\frac{\tau_i^3}{2}\frac{\rho}{F_\pi^2}2c_3\frac{1}{4m_\pi^2+p^2}(\mathbf{p}\cdot\sigma_i)\mathbf{p} = -g_A\frac{\tau_i^3}{2}\frac{\delta a_1^P(p^2)}{p^2}(\mathbf{p}\cdot\sigma_i)\mathbf{p}$$

Renormalize isovector couplings: reduce axial and enhance pseudoscalar

SD Structure Factors with 1b+2b currents



Klos, JM, Gazit, Schwenk
PRD88 083516(2013)

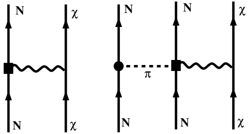


In $^{129,131}_{\ \ 54}$Xe $\langle S_n \rangle \gg \langle S_p \rangle$,
Neutrons carry most nuclear spin

Couplings sensitive more to protons ($a_0 = a_1$) or neutrons ($a_0 = -a_1$)

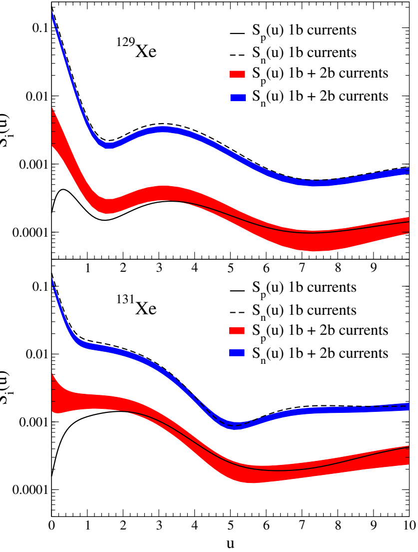
$$S(0) \propto \left| \frac{a_0+a_1}{2} \langle S_p \rangle + \frac{a_0-a_1}{2} \langle S_n \rangle \right|^2$$

2b currents involve neutrons + protons:



Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

SD Structure Factors with 1b+2b currents



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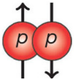

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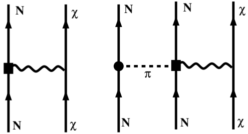
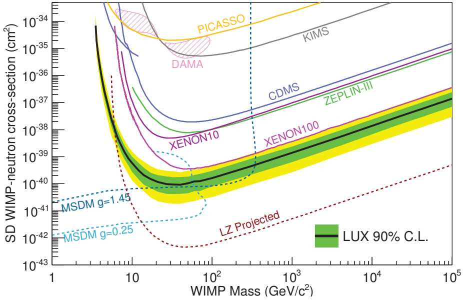
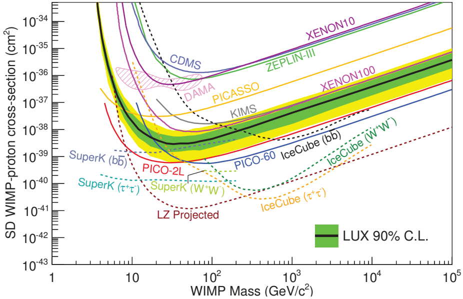


Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

Application to experiment: LUX, XENON100





Our calculations used by
LUX and XENON100 Collaborations
to set limits on
WIMP-nucleon cross-sections

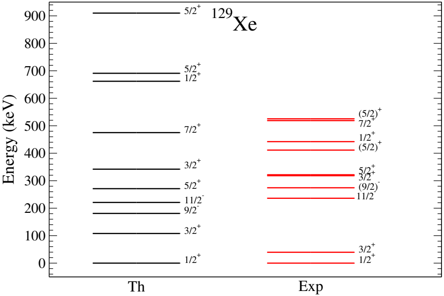
LUX obtained world best limits
for spin-dependent scattering
with “neutron” couplings

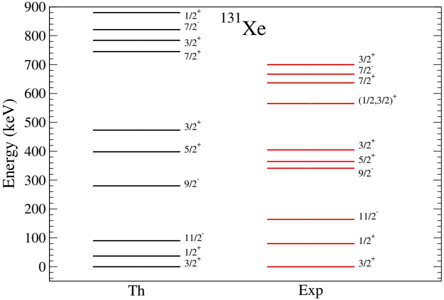
For “proton” couplings
LUX experiment is also competitive
due to the effect of 2b currents

LUX Collaboration arXiv:1602.03489

Inelastic scattering?

Can dark matter scatter exciting the nucleus to the first excited state?





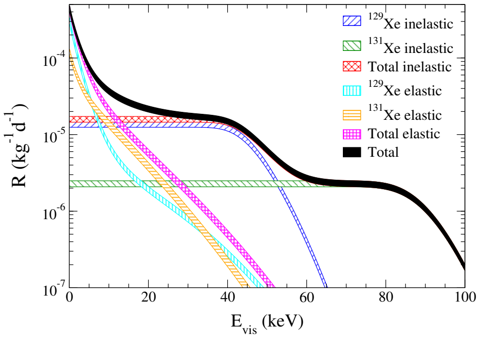
Very low-lying first-excited states $\sim 40, 80$ keV

If WIMPs have enough kinetic energy
inelastic scattering possible

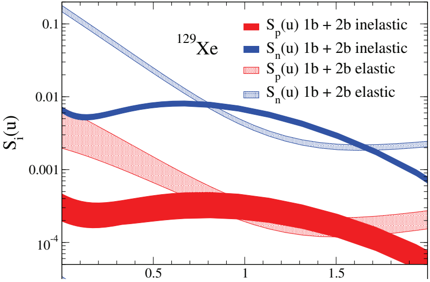
$$p_{\pm} = \mu v_i \left(1 \pm \sqrt{1 - \frac{2E^*}{\mu v_i^2}} \right)$$

Spin-dependent inelastic WIMP scattering

Inelastic structure factors
compete with elastic at $p \sim 150$ MeV,
in the kinematically allowed region



Baudis et al. PRD88 115014 (2013)



Integrated spectrum for xenon shows expected signal from inelastic scattering including the gamma from excited state decay

One plateau per excited state

Inelastic scattering ⇒ spin coupling
Density coupling suppressed:
coherence of all nucleons lost

Summary

Shell Model calculations based on chiral effective field theory including NN+3N forces and many-body perturbation theory

- 3N forces explain dripline in O, shell evolution in Ca, spectroscopy
- Theoretical uncertainties: initial Hamiltonian dominates many-body approach, limit predictive power of calculations

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

- Shell Model matrix elements smaller than other approaches, enlarging the configuration space moderate 30% increase in ^{48}Ca
- Correlations (deformation, proton-neutron pairing) have strong impact on (reducing) matrix elements
- 2b currents, analogue of 3N forces, modify nuclear matrix elements

WIMP scattering off nuclei for direct dark matter detection experiments

- Spin-Independent response coherent enhancement, no inelastic signal
- Spin-Dependent case sensitive to nuclear structure and 2b currents

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