Neutrinoless $\beta\beta$ decay and direct dark matter detection

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INT workshop "From nucleons to nuclei: enabling discovery for neutrinos, dark matter and more"

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Graduate School of Science
University of Tokyo
Center for Nuclear Study (CNS)

東京大学
THE UNIVERSITY OF TOKYO

科研費
KAKENHI

Nuclear physics, $\beta\beta$ decay, dark matter detection

Nuclear structure crucial for design and interpretation of experiments

Neutrinos, dark matter studied in low-energy experiments using nuclei

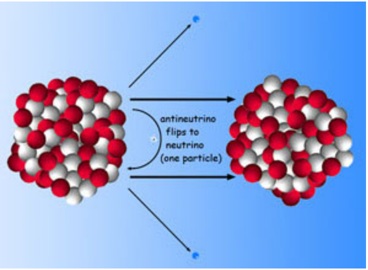
Abundant material, long observation time with very low background sensitive to rarest decays and tiny cross-sections!

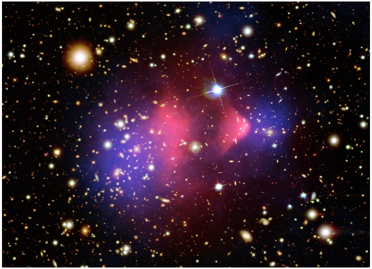
$0\nu\beta\beta$ decay: $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$

Dark matter: $\dfrac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2} \propto \left|\sum_i c_i\, \zeta_i\, \mathcal{F}_i\right|^2$

$M^{0\nu\beta\beta}$: Nuclear matrix element

$\mathcal{F}_i$: Nuclear structure factor





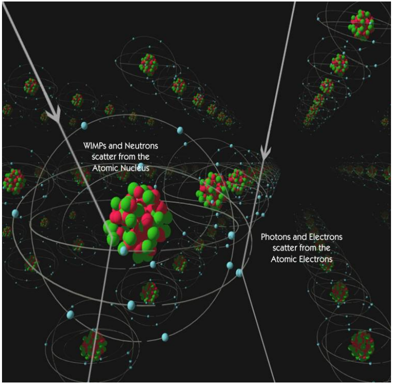
Nuclear matrix elements and structure factors

Nuclear matrix elements 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:
  Quantum Monte Carlo,
  no-core shell model, coupled cluster
  shell model, energy density functional

- Lepton-nucleus interaction:
  Evaluate (non-perturbative)
  hadronic currents inside nucleus:
  phenomenology, effective theory



CDMS Collaboration

Outline

1. Lepton number violation, neutrino nature: neutrinoless $\beta\beta$ decay
2. Direct detection of dark matter: dark matter scattering off nuclei
3. Summary

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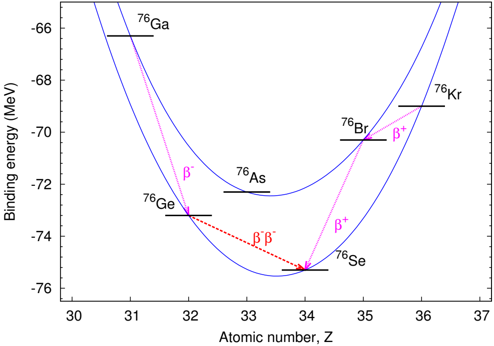
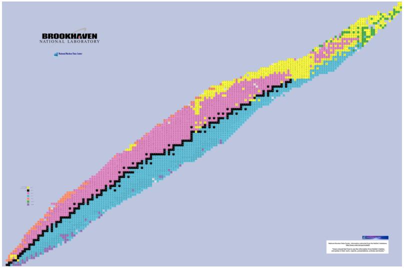
Neutrinoless $\beta\beta$ decay

Lepton-number violation, Majorana nature of neutrinos

Second order process only observable in rare cases with β-decay energetically forbidden or hindered by ΔJ



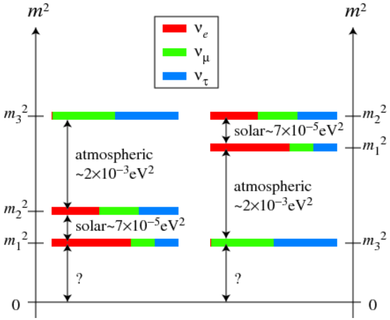


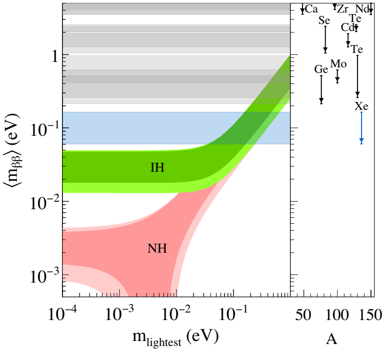
Best limits: ^{76}Ge (GERDA), ^{130}Te (CUORE), ^{136}Xe (EXO, KamLAND-Zen)

Next generation experiments: inverted hierarchy

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

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





Matrix elements needed to make sure next generation ton-scale experiments fully explore "inverted hierarchy"

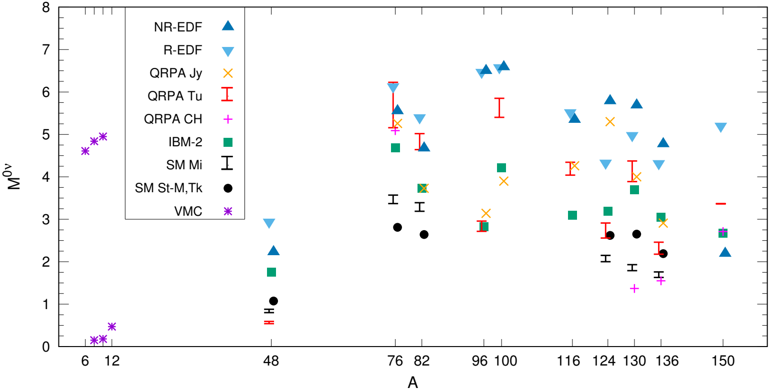
KamLAND-Zen, PRL117 082503(2016)

$0\nu\beta\beta$ decay nuclear matrix elements

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

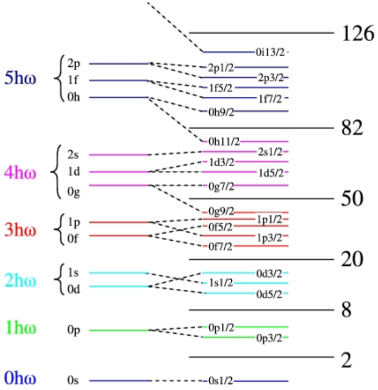
$$\langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\, \Omega^X \, | 0_i^+ \rangle$$

Ω^X = Fermi ($\mathbb{1}$), GT ($\sigma_n \sigma_m$),Tensor
$H(r)$ = neutrino potential



Ab initio quantum Monte Carlo $0\nu\beta\beta$: Pastore et al. PRC97 014606(2018)
Phenomenological many-body: shell model, energy-density functional theory, QRPA...

Shell model



Solve many-body problem
by direct diagonalization
in limited configuration space

- Excluded orbitals: always empty
- Valence space:
  configuration space where to
  solve the many-body problem
- Inner core: always filled

Diagonalize valence space,
other effects in H_{eff}:

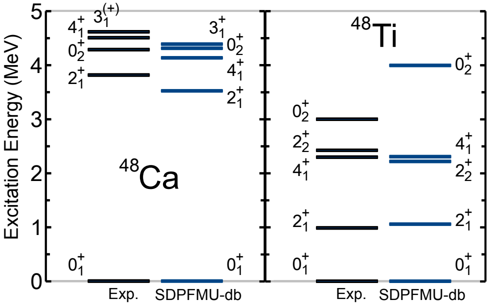
$$H\left|\Psi\right\rangle = E\left|\Psi\right\rangle \;\rightarrow H_{eff}\left|\Psi\right\rangle_{eff} = E\left|\Psi\right\rangle_{eff}$$

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

Exact diagonalization: 10^{11} dimension Caurier et al. RMP77 427 (2005)
Monte Carlo shell model: 10^{23} dimension Togashi et al. PRL117 172502 (2016)

Shell model configuration space: spectra

For ^{48}Ca enlarge shell model configuration space
from *pf* to *sdpf* (4 to 7 orbitals) restricted to $2\hbar\omega$ excitations
dimension of ^{48}Ti calculation increases from less than 10^6 to over 10^9



Iwata et al. PRL116 112502 (2016)

The 0_2^+ state in ^{48}Ca is brought down by 1.3 MeV in the *sdpf* calculation

Good agreement to experiment and with the associated two-proton transfer cross section ($2\hbar\omega$ states dominant in ^{48}Ca 0_2^+)

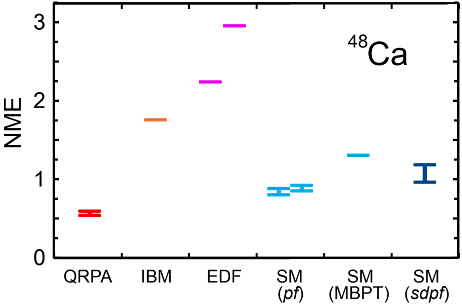
The difference in the ^{48}Ca two-neutrino $\beta\beta$ decay matrix element
is about 5% between *pf* and *sdpf* calculations

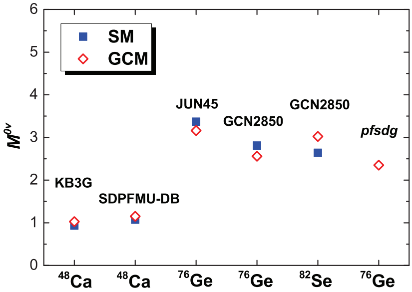
Shell model matrix elements in two shells

^{48}Ca$\rightarrow^{48}$Ti $0\nu\beta\beta$ decay

Enlarge configuration space from *pf* to *sdpf*, 4 to 7 orbitals

Test excitation energy of 0_2^+ in ^{48}Ca off by 1.3MeV in *pf* shell





Nuclear matrix element increases moderately 30%

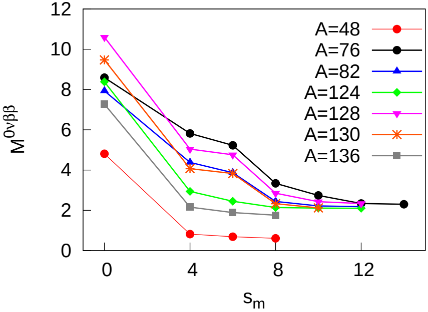
Iwata et al. PRL116 112502 (2016)

Likewise, very mild effect found in GCM calculations of ^{76}Ge

Jiao et al. PRC96 054310 (2017)

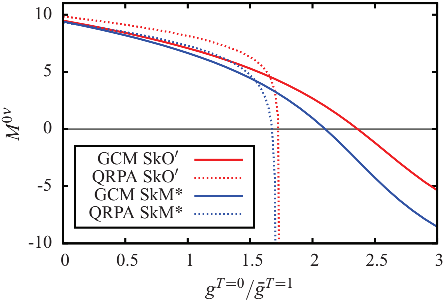
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing,
but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix element value

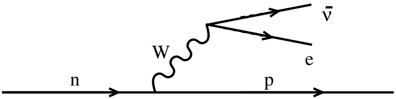


Hinohara, Engel PRC90 031301 (2014)

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

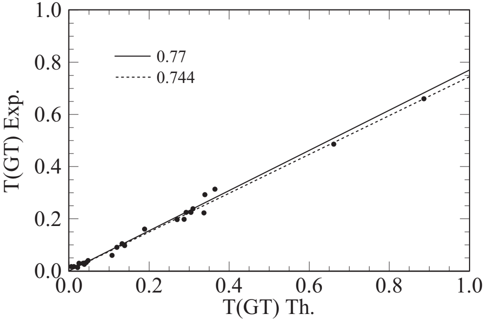
Gamow-Teller β decay: "quenching"

Gamow-Teller β decays described well by nuclear structure (shell model) but...



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

$$g_A^{\text{eff}} = q g_A, \quad q \sim 0.7 - 0.8.$$



Martínez-Pinedo et al. PRC53 2602 (1996)

Theory needs to "quench" $\boldsymbol{\sigma}\tau$ operator to reproduce experimental lifetimes: problem in nuclear many-body wf or operator?

This puzzle has been the target of many theoretical efforts:

Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...

Ab initio many-body methods

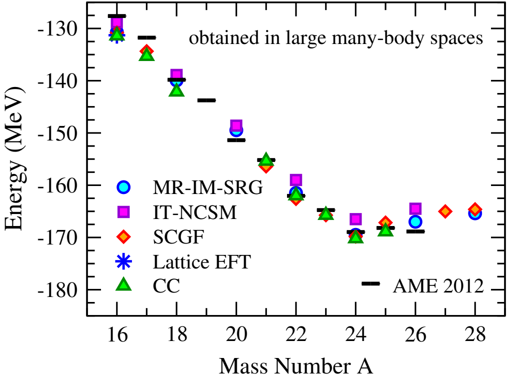
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

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-clusters
Jansen et al. PRL113 142502(2014)

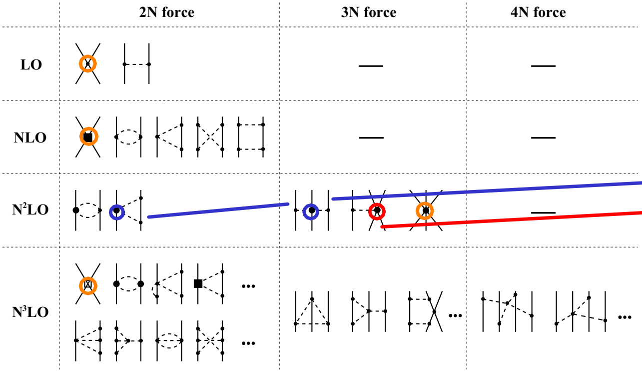


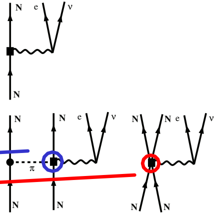
Chiral effective field theory

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, Baroni, Krebs...

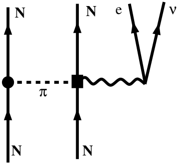
2b currents applied to
νd scattering (SNO),
^{3}H β-decay, μ moment...

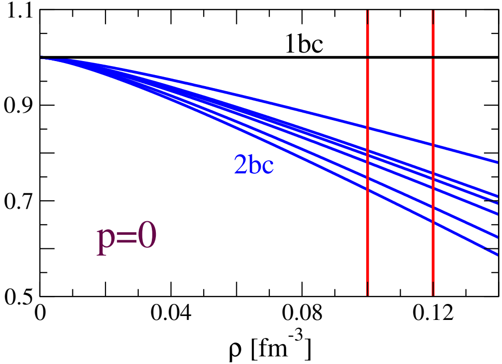
2b currents in medium-mass nuclei

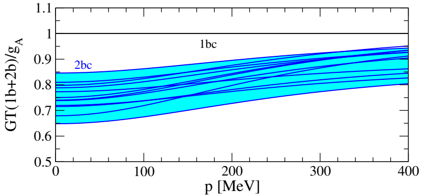
Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

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







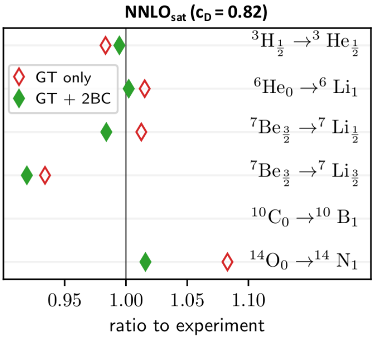
2b currents predict g_A quenching $q = 0.85...0.66$

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

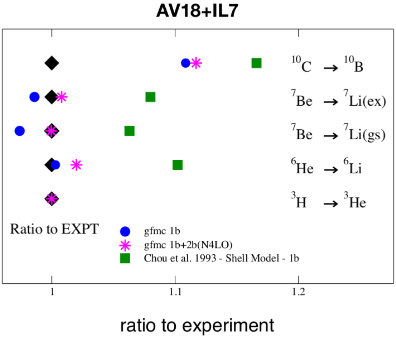
β decay in very light nuclei: GFMC vs NCSM

Quantum Monte Carlo, No Core Shell Model β decays in $A \leq 10$

G. Hagen, J. Holt, P. Navrátil et al. INT-18-1a program, Pastore et al. PRC97 022501 (2018)



No-core shell model



Quantum Monte Carlo

Very good agreement to experiment, except ^{10}C (structure)

Impact of 2b currents small (few %), disagreement on sign

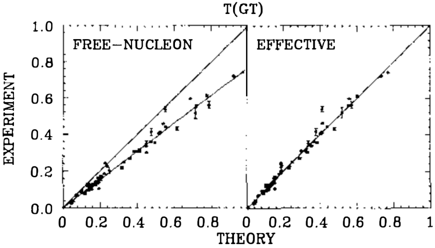
TRIUMF

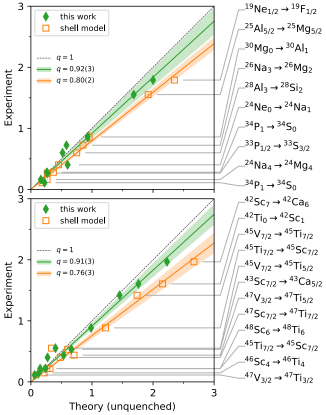
"Quenching" of g_A in Gamow-Teller Decays

VS-IMSRG calculations of GT transitions in sd, pf shells

Minor effect from consistent effective operator

Significant effect from neglected 2-body currents





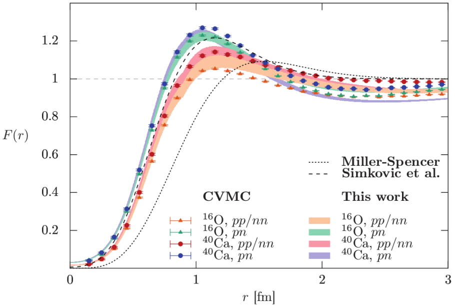
Ab initio calculations explain data with unquenched g_A

From J. Holt, INT-18-1a program

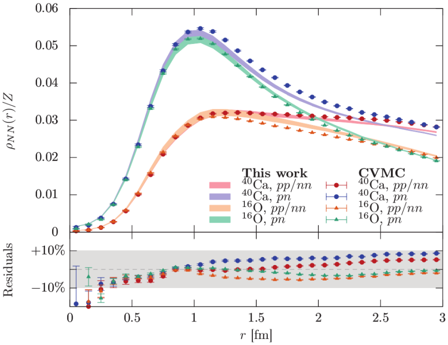
Short-range correlations

Pair correlations of
quantum Monte Carlo calculations
approximated by combination of
short- and long-range parts

$$\rho_{NN}(r) = a\,\rho_{NN}^{\text{contact}}(r) + b\,\rho_{NN}^{(0)}(r)$$



Cruz-Torres et al. arXiv:1710.07966



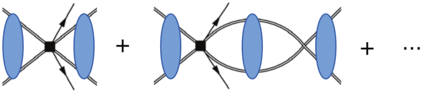
Correlation function defined by

$$F(r) = \frac{\rho_{NN}(r)}{\rho_{NN}^{\text{uncorrelated}}(r)}$$

Impact on $0\nu\beta\beta$ decay
nuclear matrix elements small $\sim 10\%$

Open questions: transition operator

Contact light-neutrino operator

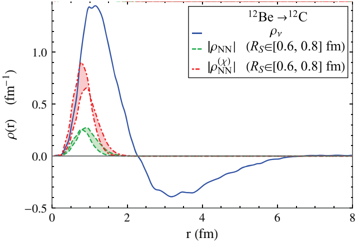


Cirigliano et al. PRL120 202001(2018)

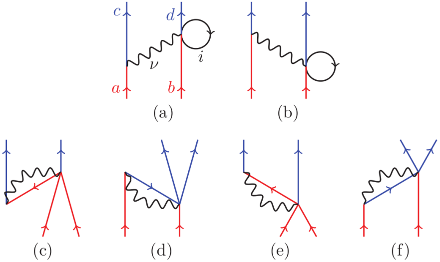
Unknown coupling value

E. Mereghetti's talk

Short-range character



Two-body currents in $\beta\beta$ decay



Estimated effect ∼ 10%

Wang et al. arXiv:1805:10276

compared to ∼ 20% in GT β decay ("quenching")

JM et al. PRL107 062501(2011)

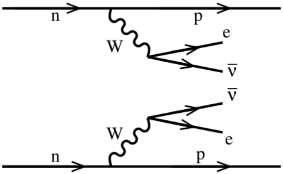
Tests of nuclear structure

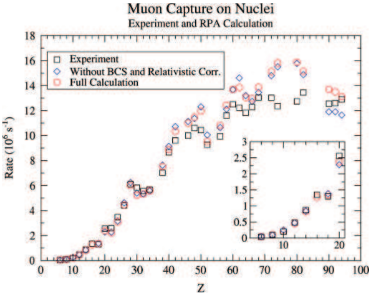
Test of $0\nu\beta\beta$ decay: comparison of predicted $2\nu\beta\beta$ decay vs data, momentum transfers $q \sim 100$ MeV: μ-capture, inelastic ν scattering

Shell model reproduce $2\nu\beta\beta$ data including "quenching" common to β decays in same mass region

$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \sigma_n \tau_n^- | 1_k^+ \rangle \langle 1_k^+ | \sum_m \sigma_m \tau_m^- | 0_i^+ \rangle}{E_k - (M_i + M_f)/2}$$

Shell model prediction previous to ^{48}Ca measurement!

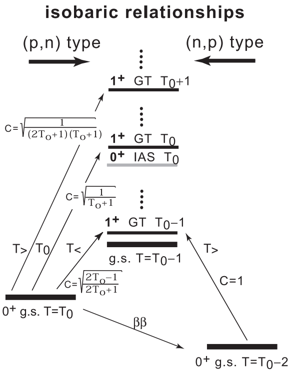




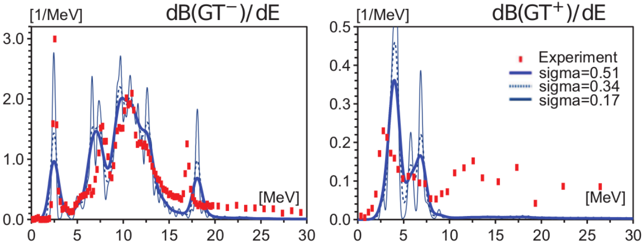
μ-capture, ν-nucleus scattering
many multipoles (J values), like $0\nu\beta\beta$ decay

Gamow-Teller strength distributions

Gamow-Teller (GT) strength distributions well described by theory (quenched)



Freckers et al.
NPA916 219 (2013)



Iwata et al. JPSCP 6 03057 (2015)

$$\frac{d\sigma}{d\Omega}(\theta=0) \propto \sum_i \boldsymbol{\sigma}_i \tau^{\pm}$$

$$\langle 1^+_f | \sum_i g_A^{\text{eff}}\, \boldsymbol{\sigma}_i \tau_i^{\pm} | 0^+_{gs} \rangle\,, \quad g_A^{\text{eff}} \approx 0.7 g_A$$

GT strengths combined related to $2\nu\beta\beta$ decay, but relative phase unknown

Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance
in double charge-exchange reactions ^{48}Ca(pp,nn)^{48}Ti proposed in 80's

Auerbach, Muto, Vogel... 1980's, 90's

Recent experimental plans in RCNP, RIKEN (^{48}Ca), INFN Catania

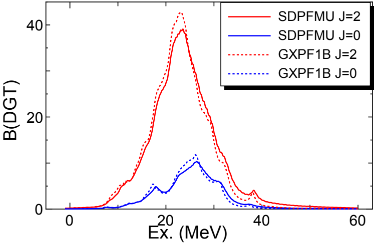
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

Capuzzello et al. EPJA 51 145 (2015), Takahisa, Ejiri et al. arXiv:1703.08264

Promising connection to $\beta\beta$ decay,
two-particle-exchange process,
especially the (tiny) transition
to ground state of final state

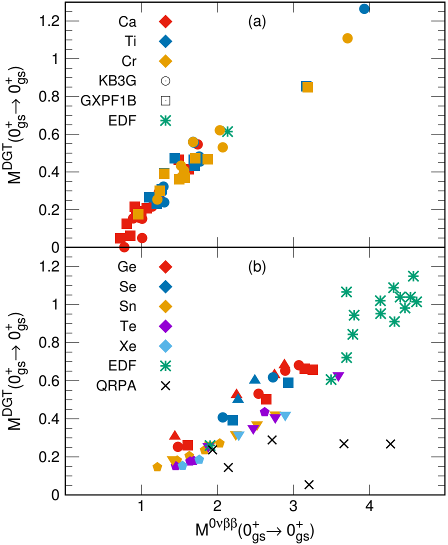
Shell model calculation

Shimizu, JM, Yako, PRL120 142502 (2018)



$$B(DGT^-;\lambda;i\rightarrow f)=\frac{1}{2J_i+1}\left|\left\langle {}^{48}\mathrm{Ti}\right|\right|\left[\sum_i \boldsymbol{\sigma}_i\tau_i^- \times \sum_j \boldsymbol{\sigma}_j\tau_j^-\right]^{(\lambda)}\left|\right|{}^{48}\mathrm{Ca}_{gs}\left.\right\rangle\Big|^2$$

DGT and $0\nu\beta\beta$ decay: heavy nuclei



DGT transition to ground state

$$M^{\mathrm{DGT}} = \sqrt{B(DGT_-; 0; 0^+_{gs} \rightarrow 0^+_{gs})}$$

very good linear correlation with $0\nu\beta\beta$ decay nuclear matrix elements

Correlation holds across wide range of nuclei, from Ca to Ge and Xe

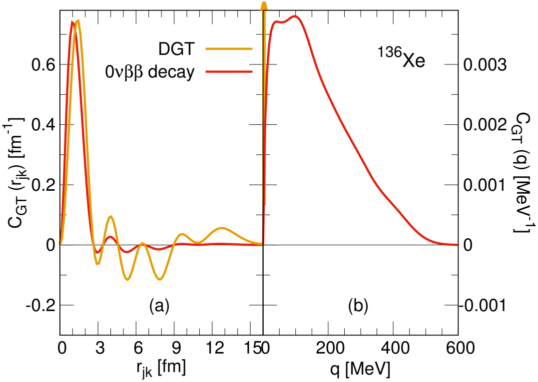
Common to shell model and energy-density functional theory $0 \lesssim M^{0\nu\beta\beta} \lesssim 5$ disagreement to QRPA

Shimizu, JM, Yako, PRL120 142502 (2018)

Short-range character of DGT, $0\nu\beta\beta$ decay

Correlation between DGT and $0\nu\beta\beta$ decay matrix elements explained by transition involving low-energy states combined with dominance of short distances between exchanged/decaying neutrons

Bogner et al. PRC86 064304 (2012)



$0\nu\beta\beta$ decay matrix element limited to shorter range

Short-range part dominant in double GT matrix element due to partial cancellation of mid- and long-range parts

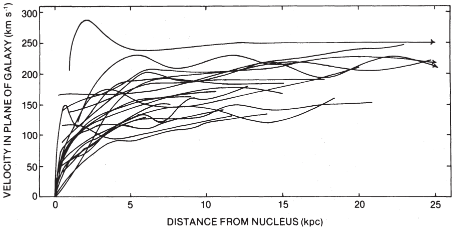
Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako, PRL120 142502 (2018)

Outline

1. Lepton number violation, neutrino nature: neutrinoless $\beta\beta$ decay
2. Direct detection of dark matter: dark matter scattering off nuclei
3. Summary

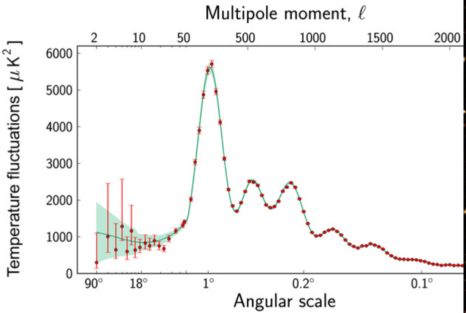
Dark matter: evidence

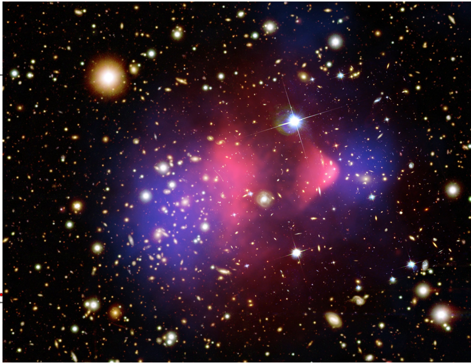


Solid cosmological evidence
for existence of dark matter
in very different observations:

Rotation curves, Lensing, CMB...

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

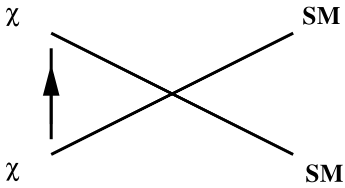




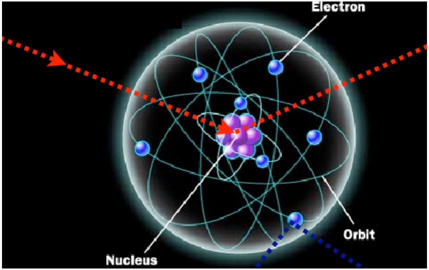
Direct detection of dark matter

Challenge: direct detection of dark matter in the laboratory
to understand its nature / composition

Assume dark matter (WIMPs)
interact with quarks, gluons
$\Rightarrow$
direct detection possible
via scattering off nuclear targets



International collaborations:
XENON, LUX, PANDA-X, CDMS...
measure nuclear recoils
from WIMP-nucleus scattering
sensitive to $m_\chi \gtrsim 1$ GeV

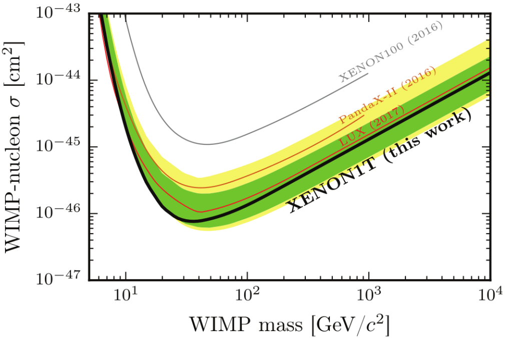


Theory: most efficient analysis of
experiments covering widest range of
WIMP-nucleus interactions

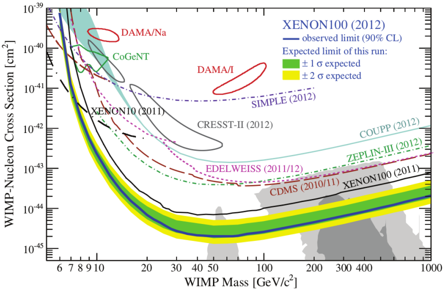
Direct dark matter detection exclusion plots

Present experiments show no evidence for dark matter,
in spite of some unconfirmed claims

Exclusion plots restrict dark matter coupling to Standard Model fields



XENON Coll. PRL119 181301 (2017)



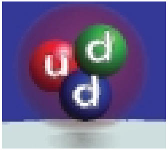
XENON Coll. PRL109 181301 (2012)

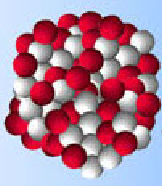
Standard analyses consider simplest “spin-independent” (scalar-scalar)
and sometimes “spin-dependent” (axial-axial) isovector couplings

Particle, hadronic and nuclear physics

WIMP scattering off nuclei
interplay of particle, hadronic and nuclear physics:

WIMPs: interaction with quarks and gluons
Quarks and gluons: embedded in the nucleon
Nucleons: form complex, many-nucleon nuclei





General WIMP-nucleus scattering cross-section:

$$\frac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2} \propto \left| \sum_i c_i \, \zeta_i \, \mathcal{F}_i \right|^2$$

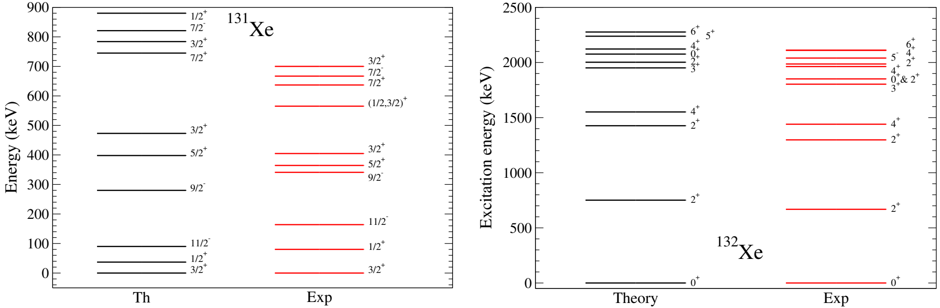
ζ: kinematics $(q^2, \cdots)$

c coefficients:
WIMP couplings to quark, gluons (Wilson coefficients), particle physics
convoluted with hadronic matrix elements, hadronic physics

$\mathcal{F}$ functions: $\mathcal{F}^2 \sim$ structure factor, nuclear structure physics

Nuclear structure for xenon

For xenon, phenomenological shell model
(part of the) nuclear interaction adjusted to nuclei in same mass region



JM, Gazit, Schwenk PRD86 103511(2012)

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

Agreement to experimental excitation spectra very good

Calculations with 5 orbitals for protons, neutrons: max dimenstion $4*10^8$

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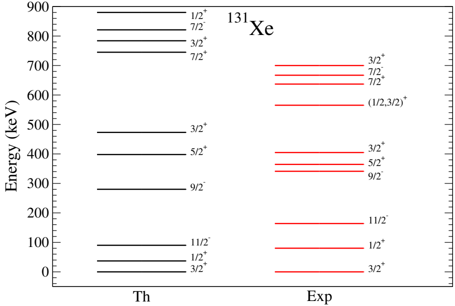
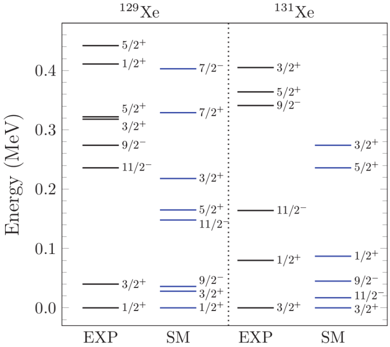




arXiv:1804.08995

JM, Gazit, Schwenk PRD86 103511(2012)

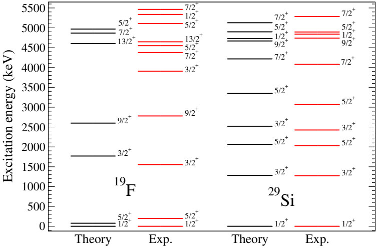
Vietze, Klos, JM, Haxton, Schwenk PRD91 043520 (2015)

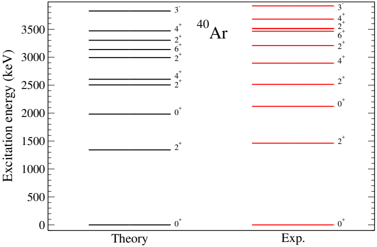
Agreement to experimental excitation spectra very good

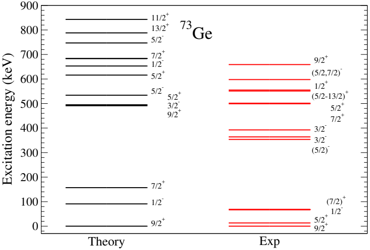
Calculations with 5 orbitals for protons, neutrons: max dimenstion $4*10^8$

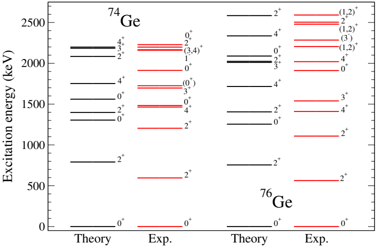
Nuclear structure for dark matter scattering targets

Similar level of agreement in other light / medium-mass nuclei studied









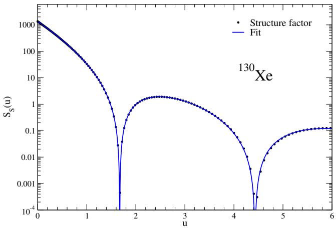
WIMP scattering off nuclei: standard analysis

Standard direct detection analyses consider two very different cases

Spin-Independent (SI) interaction:
WIMPs couple to the nuclear density ($\mathbb{1}_\chi \mathbb{1}_N$)

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

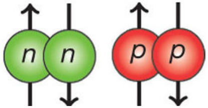
Cross section enhancement by factor
$|\sum_A \langle \mathcal{N} \| \mathbb{1}_N | \mathcal{N} \rangle|^2 = A^2$



Spin-Dependent (SD) interaction:
WIMP spins couple to the nuclear spin ($\mathbf{S}_\chi \cdot \mathbf{S}_N$)

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

Cross section scale set by single-proton/neutron spin expectation value
$|\sum_A \langle \mathcal{N} \| \mathbf{S}_N | \mathcal{N} \rangle|^2 = \langle \mathbf{S}_n \rangle^2, \langle \mathbf{S}_p \rangle^2 \sim 0.1$



Non-relativistic effective field theory

SI and SD interactions only consider the leading-order operators ($\mathcal{O}_1$, $\mathcal{O}_4$) in the non-relativistic basis spanned by $\mathbb{1}_\chi$, $\mathbb{1}_N$, $\boldsymbol{S}_N$, $\boldsymbol{S}_\chi$, $\mathbf{q}$, $\mathbf{v}^\perp$

$$\mathcal{O}_1 = 1_\chi 1_N,$$
$$\mathcal{O}_2 = (v^\perp)^2,$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N,$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp,$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N},$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}.$$
$$\ldots$$

Fitzpatrick et al. JCAP02 004(2013), Anand et al. PRC89 065501 (2014)

Interferences occur between some of the terms,
which map into 6 different nuclear responses
M (SI scattering), Σ, Σ' (SD scattering), Δ, Φ", $\tilde{\Phi}$' (new responses)

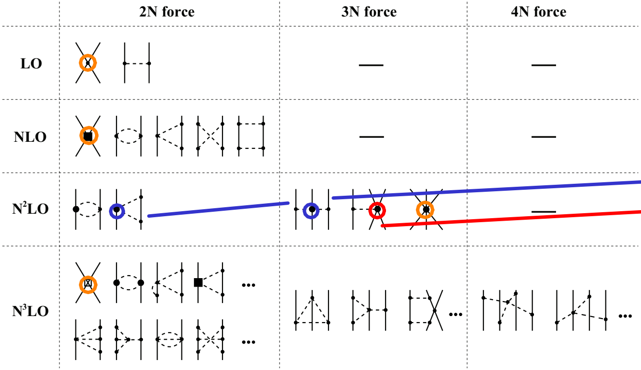
⇒ nuclear structure calculations to interpret dark matter detection data

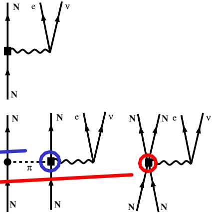
Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and currents





Park et al.
PRC67 055206(2003)

Short-range couplings fitted to experiment once

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

Chiral EFT WIMP-nucleus interactions

WIMP–quark/gluon 1b+2b interactions at hadronic scale, map into NREFT

WIMP	Nucleon	V t	V **x**	A t	A **x**
V	1b	0	1 + 2	2	0 + 2
	2b	4	2 + 2	2	4 + 2
	2b NLO	—	—	5	3 + 2
A	1b	0 + 2	1	2 + 2	0
	2b	4 + 2	2	2 + 2	4
	2b NLO	—	—	5 + 2	3

WIMP	Nucleon	S	P
S	1b	2	1
	2b	3	5
	2b NLO	—	4
P	1b	2 + 2	1 + 2
	2b	3 + 2	5 + 2
	2b NLO	—	4 + 2

$$\mathcal{M}^{SS}_{1,\mathrm{NR}} = \mathcal{O}_1 f_N(t) \qquad \mathcal{M}^{SP}_{1,\mathrm{NR}} = \mathcal{O}_{10} g_5^N(t) \qquad \mathcal{M}^{PP}_{1,\mathrm{NR}} = \frac{1}{m_\chi}\mathcal{O}_6 h_5^N(t)$$

$$\mathcal{M}^{VV}_{1,\mathrm{NR}} = \mathcal{O}_1\left(f_1^{V,N}(t) + \frac{t}{4m_N^2} f_2^{V,N}(t)\right) + \frac{1}{m_N}\mathcal{O}_3 f_2^{V,N}(t) + \frac{1}{m_N m_\chi}\left(t\mathcal{O}_4 + \mathcal{O}_6\right) f_2^{V,N}(t)$$

$$\mathcal{M}^{AV}_{1,\mathrm{NR}} = 2\mathcal{O}_8 f_1^{V,N}(t) + \frac{2}{m_N}\mathcal{O}_9\left(f_1^{V,N}(t) + f_2^{V,N}(t)\right)$$

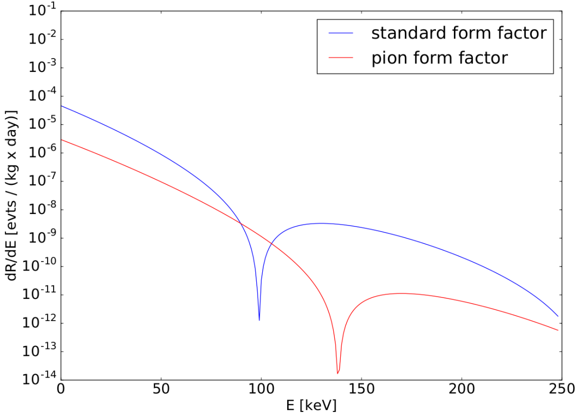
$$\mathcal{M}^{AA}_{1,\mathrm{NR}} = -4\mathcal{O}_4 g_A^N(t) + \frac{1}{m_N^2}\mathcal{O}_6 g_P^N(t) \qquad \mathcal{M}^{VA}_{1,\mathrm{NR}} = \left\{-2\mathcal{O}_7 + \frac{2}{m_\chi}\mathcal{O}_9\right\} h_A^N(t)$$

Hoferichter, Klos, Schwenk PLB 746 410 (2015)

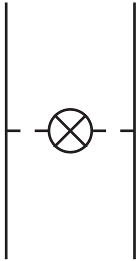
Chiral EFT hierarchy to be complemented with nuclear effects (coherence)

Dark matter coupling to two nucleons

Coherent contributions from 2b currents:
π coupling, via scalar current and energy-momentum tensor θ^μ_μ



Hoferichter et al. PRD94 063505 (2016)



2b scalar currents also explored by

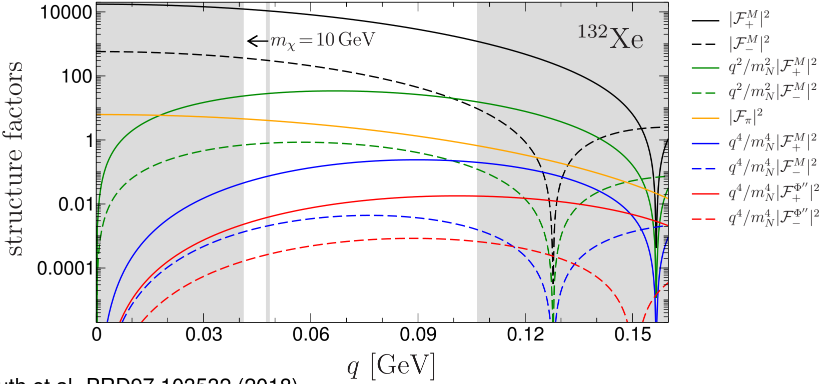
Cirigliano et al. JHEP10 25(2012)

PLB739 293(2014)

Generalized coherent scattering

Generalized spin-independent scattering cross section:

$$\frac{d\sigma^{SI}_{\chi\mathcal{N}}}{dq^2} = \frac{1}{4\pi v^2}\left|c_+^M \mathcal{F}_+^M(q^2) + c_-^M \mathcal{F}_-^M(q^2) + c_\pi \mathcal{F}_\pi(q^2) + \cdots\right|^2$$

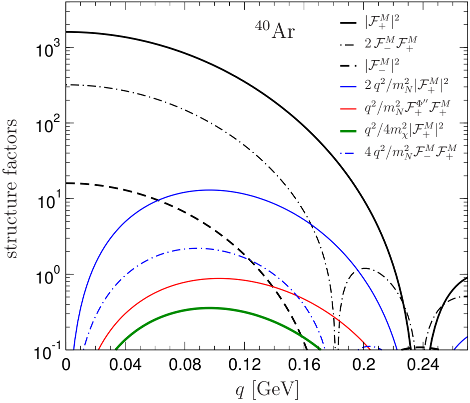


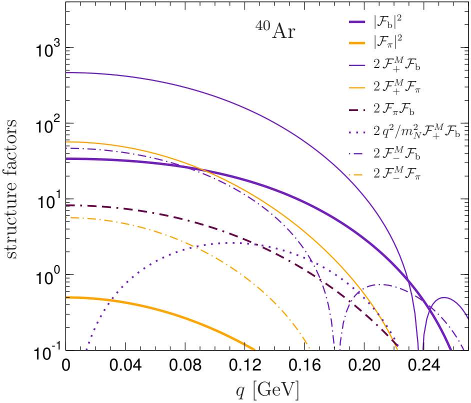
Fieguth et al. PRD97 103532 (2018)

In addition, interference terms between different contributions

Generalized coherent scattering with interferences

Many different coherent contributions when including interferences

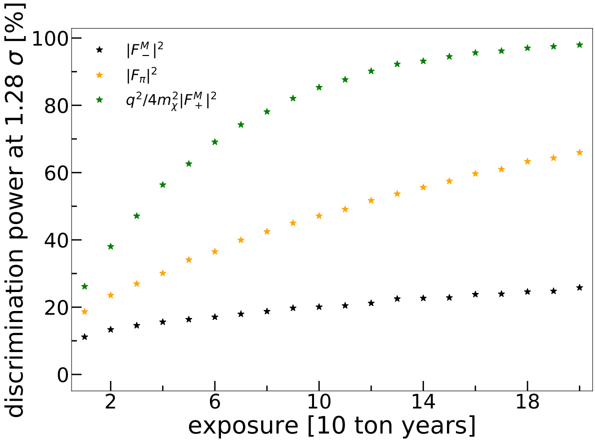




Hoferichter, Klos, JM, Schwenk, in preparation

Discriminate dark matter-nucleus interactions

Once dark matter scattering off nuclei is observed,
key to unveil nature of dark matter-nucleus interaction

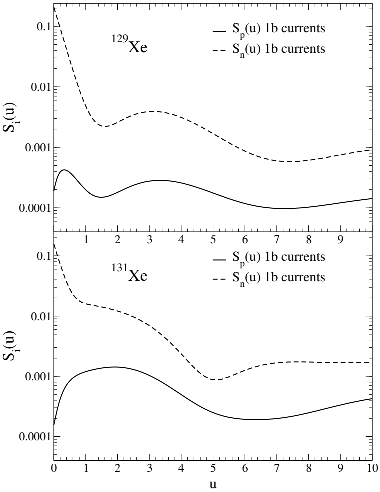


Future experiments can discriminate different interactions if markedly different q-dependence

Isoscalar / isovector character can be discriminated in nuclei with $N = Z$ vs $N \neq Z$

Fieguth et al.
PRD97 103532 (2018)

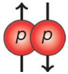
Spin-dependent scattering: coupling to one nucleon



JM, Gazit, Schwenk, PRD86 103511(2012)

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

In $^{129,131}_{54}$Xe $\langle \boldsymbol{S}_n \rangle \gg \langle \boldsymbol{S}_p \rangle$,



Neutrons carry most nuclear spin

$$\boldsymbol{S}_n = \sum_{i=1}^{N} \boldsymbol{\sigma}_i/2, \quad \boldsymbol{S}_p = \sum_{i=1}^{Z} \boldsymbol{\sigma}_i/2$$

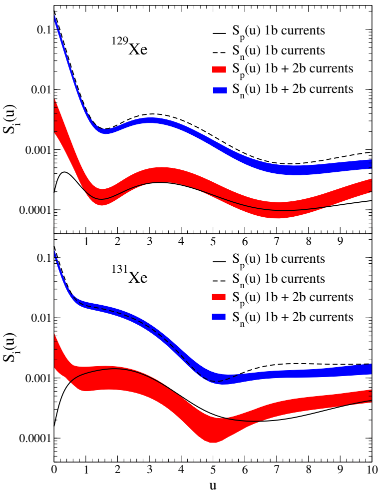
$$\frac{\mathcal{F}_A(0)^2}{2J+1} = \frac{(J+1)}{\pi J} \left| a_p \langle \boldsymbol{S}_p \rangle + a_n \langle \boldsymbol{S}_n \rangle \right|^2$$

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

$$\mathcal{F}_n(0)^2 \propto \left| \langle \boldsymbol{S}_n \rangle \right|^2, \quad \mathcal{F}_p(0)^2 \propto \left| \langle \boldsymbol{S}_p \rangle \right|^2$$

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

Spin-dependent scattering: coupling to two nucleons



JM, Gazit, Schwenk, PRD86 103511(2012)

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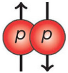
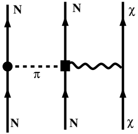


Neutrons carry most nuclear spin

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

2b currents naturally involve both neutrons and protons:

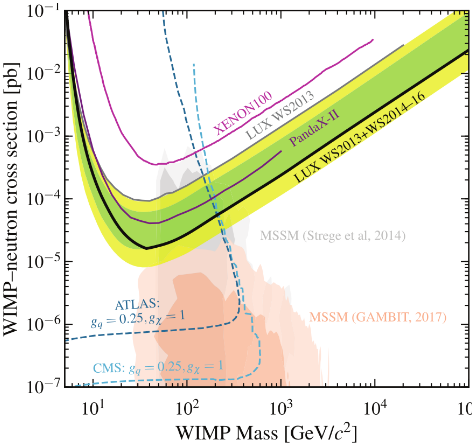


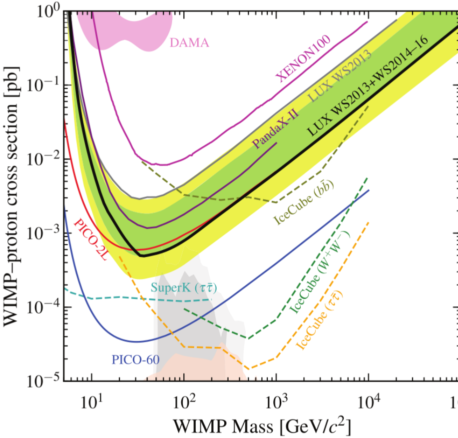
Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

Impact on dominant species $\sim 20\%$

Application to experiment

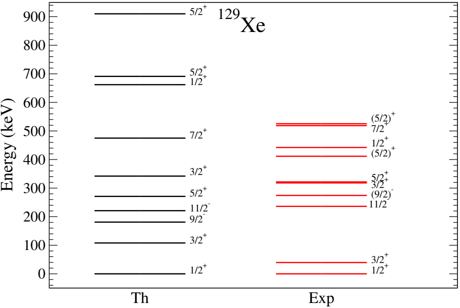
2b contributions make xenon SD results (more sensitive to neutrons) competitive for WIMP-proton cross-section LUX Coll. PRL118 251302 (2017)

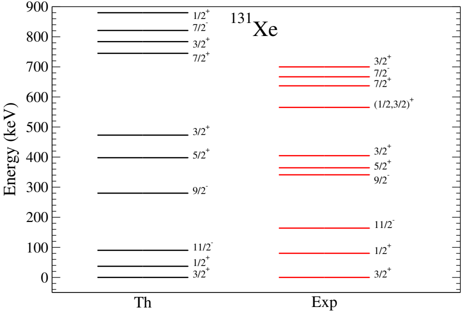




Inelastic WIMP scattering off a nucleus?

Very low-lying first-excited states $\sim 40, 80$ keV in odd-mass xenon





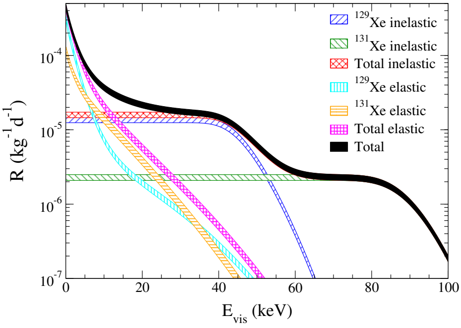
JM, Gazit, Schwenk PRD86 103511(2012)

If WIMPs have enough kinetic energy,
inelastic scattering may be possible

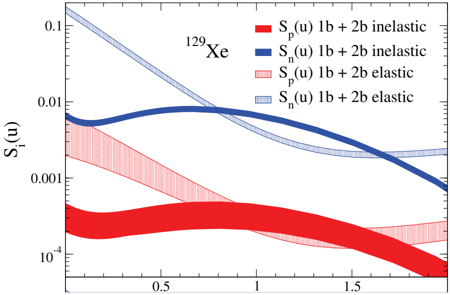
$$p_{\pm} = \mu v_i \left(1 \pm \sqrt{1 - \frac{2E^*}{\mu v_i^2}}\right)$$

Inelastic WIMP scattering off xenon

Inelastic structure factors
compete with elastic ones around
$q \sim 100$ MeV
in the kinematically allowed region



Baudis et al. PRD88 115014 (2013)



Integrated spectrum for xenon:
inelastic scattering signal
including γ-ray
from decay of excited state

One "plateau" to be detected
for each nuclear excitation

Signal of spin-dependent scattering

Outline

Summary

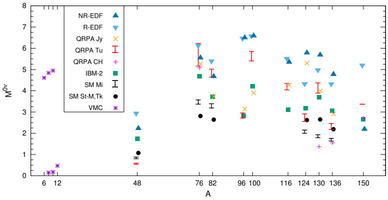
Nuclear matrix elements and structure factors key for fully exploiting $\beta\beta$ decay and direct dark matter detection experiments

Neutrinoless $\beta\beta$ decay:

Improve matrix elements in larger configuration spaces with all relevant correlations

Ab initio with 2b currents free from β decay "quenching"

Double Gamow-Teller transitions correlated to $0\nu\beta\beta$ decay

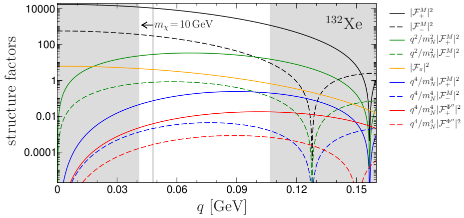


Direct dark matter detection:

Need to consider generalized WIMP-nucleon couplings discriminated by q-dependence

2b currents WIMP coupling to pion (scalar, θ coupling)

2b currents key in SD scattering



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