Nuclear structure aspects of dark matter direct detection

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東京大学 THE UNIVERSITY OF TOKYO

日本学術振興会 Japan Society for the Promotion of Science

科研費 KAKENHI

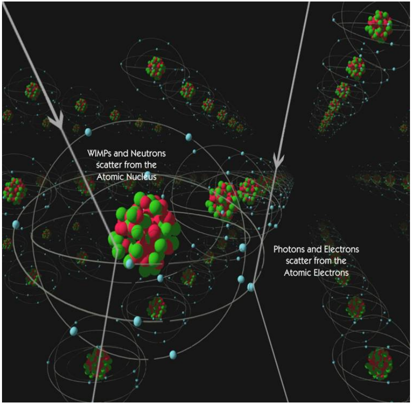
Direct dark matter detection

Overwhelming evidence dark matter exists,
the challenge is direct dark matter detection to understand its nature

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

Lots of material (10^{23} nuclei in A grams) in underground labs (low background) sensitive to very small cross-sections

Direct detection experiments:
XENON, LUX, CDMS...
nuclear recoil from WIMP scattering sensitive to dark matter with masses $m_\chi \gtrsim 1$ GeV



CDMS Collaboration

Particle, hadronic and nuclear physics scales

WIMP scattering off nuclei governed by the
interplay of particle, hadronic and nuclear physics scales:

WIMPs: new physics interaction with quarks and gluons
quarks and gluons: embedded in the nucleon
nucleons: components of nuclei, strongly interacting many-nucleon systems

General WIMP-nucleus scattering cross-section:

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

c coefficients: convolution of
WIMP couplings to quark, gluons (Wilson coefficients), particle physics
and hadronic matrix elements, hadronic physics

R. Hill, M. Hoferichter talks

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

This talk

ζ: kinematics $(q^2, \cdots)$

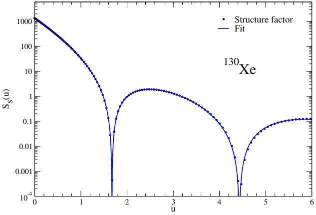
WIMP scattering off nuclei: standard analysis

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

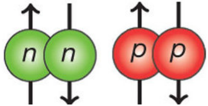
Cross section enhancement by factor
$|\sum_A \langle \mathcal{N} || \mathbb{1}_N | \mathcal{N} \rangle|^2 = A^2$



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

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
$|\sum_A \langle \mathcal{N} || \boldsymbol{S}_N | \mathcal{N} \rangle|^2 = \langle \boldsymbol{S}_n \rangle^2, \langle \boldsymbol{S}_p \rangle^2 \sim 0.1$



How can direct detection analyses be generalized?

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 $\mathbb{1}_\chi$, $\mathbb{1}_N$, $\boldsymbol{S}_N$, $\boldsymbol{S}_\chi$, **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 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

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

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

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

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

Hoferichter, Klos, Schwenk PLB 746 410 (2015), **talk by M. Hoferichter**

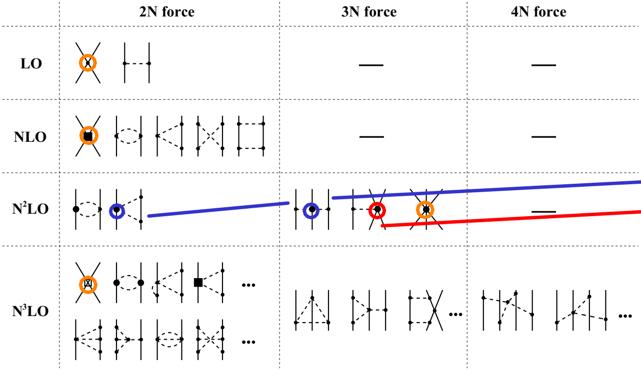
Chiral EFT hierarchy to be complemented with nuclear effects (coherence)

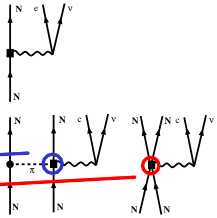
Chiral effective field theory

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...

Oxygen ab-initio calculations

Oxygen isotopes with chiral NN+3N forces, solving *A*-body problem

Agreement of very different many-body methods:

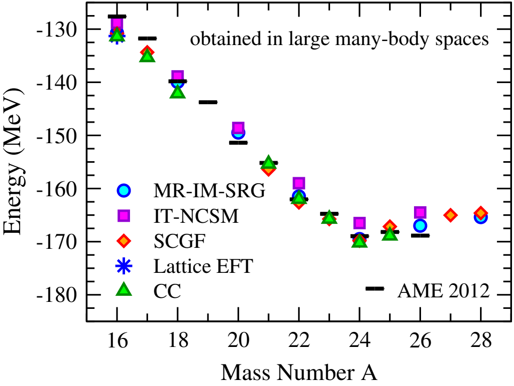
No-core shell model (Importance-truncated)
Roth et al. PRL107 072501 (2011)

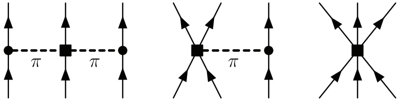
In-medium SRG
Hergert et al. PRL110 242501 (2013)

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

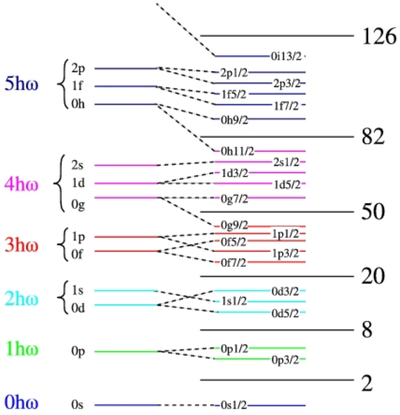
Coupled-cluster
Jansen et al. PRL113 142502 (2014)

Lattice effective field theory
Epelbaum et al. PRL112 102501 (2014)





Shell Model



The Shell Model solves the many-body problem by direct diagonalization in a relatively small configuration space

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

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

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

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

Exact diagonalization: 10^{11} dimension Caurier et al. RMP77 427 (2005)

Monte Carlo shell model: 10^{23} dimension Togashi et al. arXiv:1606.09056

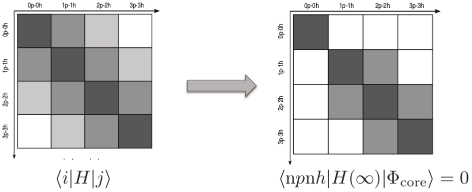
Ab initio shell model

Effective interaction, with effects beyond valence space
obtained perturbatively, or nonperturbatively from chiral EFT NN+3N forces

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

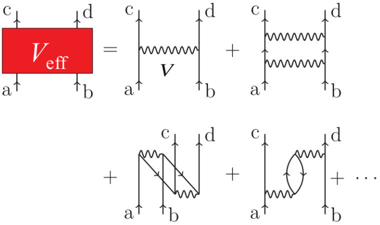
In-medium SRG

Bogner, Hergert, Schwenk, Stroberg...



Many-body perturbation theory

Hjorth-Jensen, Holt...



Coupled Cluster Jansen, Hagen...

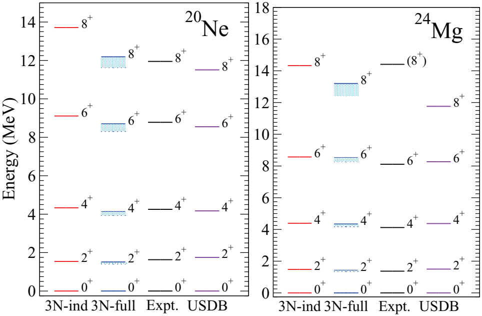
Solve Reference state (core), $A+1$ and $A+2$ systems

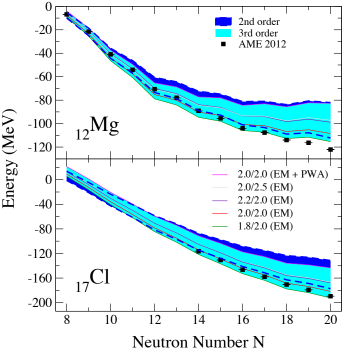
Project coupled-cluster solution to valence space (Okubo-Lee-Suzuki transf.)

Correlated systems and theoretical uncertainties

Light, correlated (deformed) comparable to phenomenlogical interactions

Based on chiral EFT forces
ab-initio-based methods are able to estimate theoretical uncertainties

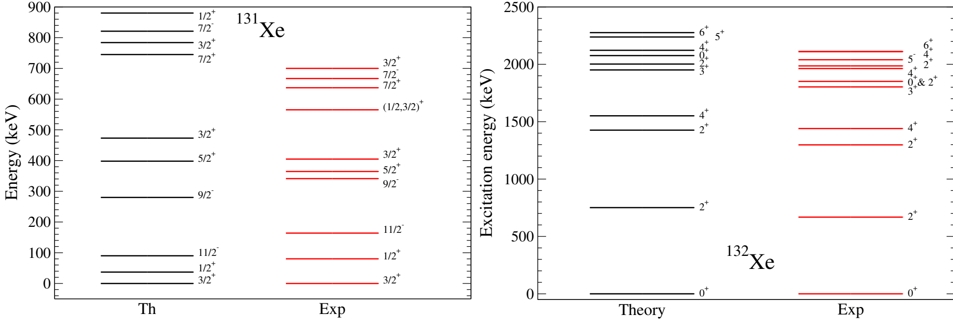




MBPT: Simonis et al. PRC93 011302 (2016)
IM-SRG: Stroberg et al. PRC93 051301 (2016)
CCEI: Jansen et al. PRC94 011301 (2016)

Shell model (phenomenological)

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



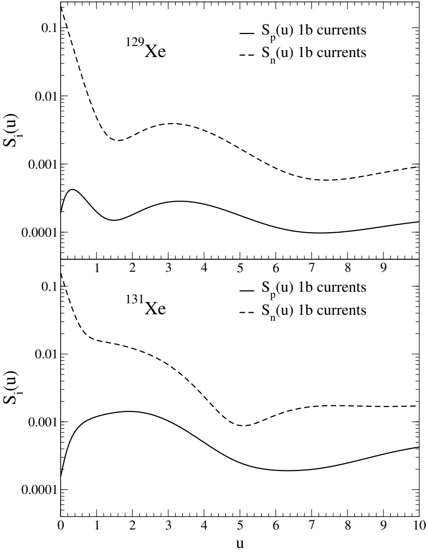
JM, Gazit, Schwenk PRD86 103511(2012)

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

Agreement to experimental excitation spectra very good

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

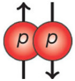
SD structure factors with 1b currents



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

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

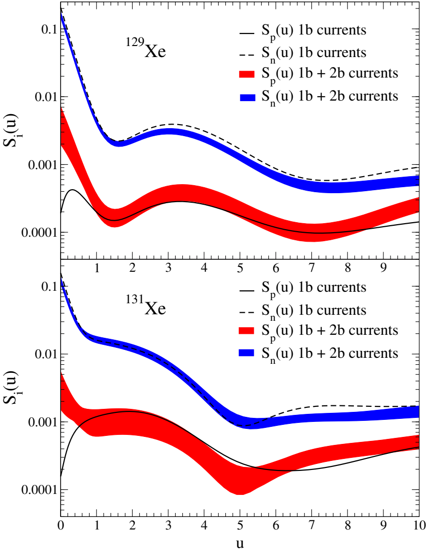
$$\frac{S_A(0)}{2J+1} = \frac{(J+1)}{\pi J} \left| a_p \langle \boldsymbol{S}_p \rangle + a_n \langle \boldsymbol{S}_n \rangle \right|^2$$

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

$$S_n(0) \propto \left| \langle \boldsymbol{S}_n \rangle \right|^2 \; S_p(0) \propto \left| \langle \boldsymbol{S}_p \rangle \right|^2.$$

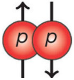
Couplings more sensitive to protons ($a_0 = a_1$) or neutrons ($a_0 = -a_1$)

SD structure factors with 1b+2b currents



JM, Gazit, Schwenk, PRD86 103511(2012)

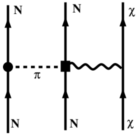
Klos, JM, Gazit, Schwenk, PRD88 083516(2013)

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

Neutrons carry most nuclear spin

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

2b currents naturally involve both neutrons and protons:

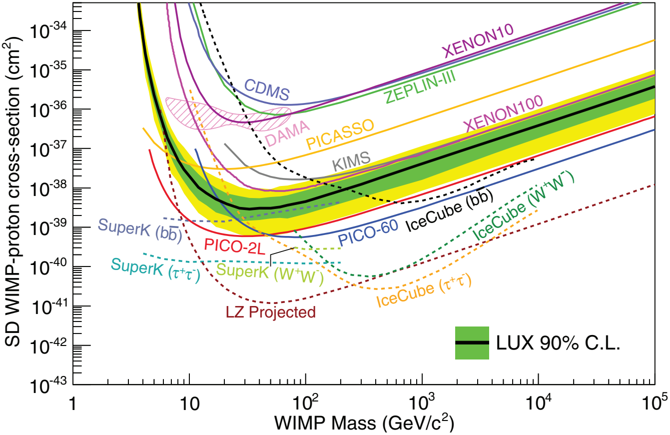


Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

Impact on dominant species $\sim$ 20%

Application to experiment: LUX

2b contributions make LUX SD results (more sensitive to neutrons) competitive also for the SD WIMP-proton cross-section



Akerib et al. PRL116 161302 (2016)

Generalized SI scattering: isovector terms

Generalized SI scattering: all coherent contributions
Separation in terms of kind of interaction less useful than SI/SD case
WIMP-spin or nucleon-spin interactions can be coherent

Study structure factors $\sim \zeta^2 \mathcal{F}^2$
responsible for coherence, assume similar c's

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

In standard SI analyses only isovector $\mathcal{O}_1$ response

Isoscalar structure factor: $A^2 \sim 130^2$

Isovector structure factor: $(N-Z)^2 \sim 30^2$

Isoscalar-Isovector interference: $A(N-Z) \sim 130 * 30$

Isovector counterpart of $\mathcal{O}_1 \sim 20\%$ correction
especially important in heavier nuclei (neutron-rich)

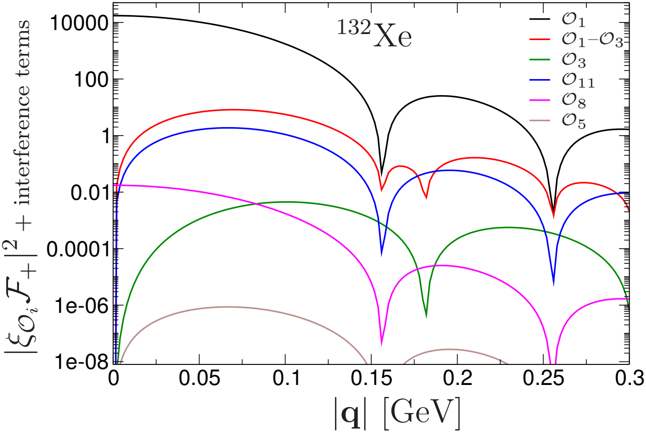
May be suppressed in models with small isospin-breaking

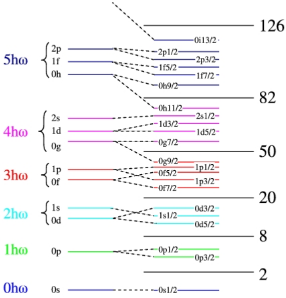
Isoscalar and isovector contributions
constrain different new physics parameters

$$c_{\pm} \propto \left(f_p \pm f_n + f_1^{V,p} \pm f_1^{V,n} \right)$$

One-body corrections: $\mathcal{O}_3$ operator

In addition to standard SI operator $\mathcal{O}_1$,
contribution from coherent $\mathcal{O}_{11,8,5}$, quasi-coherent $\mathcal{O}_3$ operator (Φ'' response)



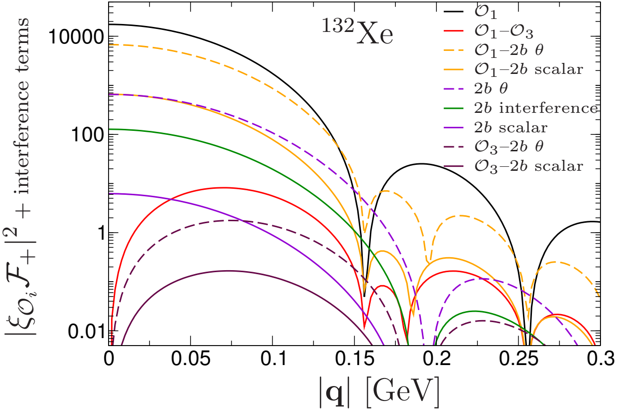


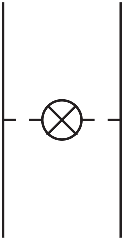
O_3 quasi-coherence:
spin ∥ ang. momentum
lower energy orbitals

$\mathcal{O}_3 \to \Phi''$ response $\sim$ nucleon spin orbit operator, interferes with $\mathcal{O}_1$
$\mathcal{O}_{11,8,5}$ suppressed by $1/m_\chi$ or $v \sim 10^{-3}$, no $\mathcal{O}_1$ interference (depend on S_χ)

Two-body currents

Two coherent contributions from 2b currents:
π coupling via scalar current, trace anomaly of energy momentum tensor (θ^μ_μ)





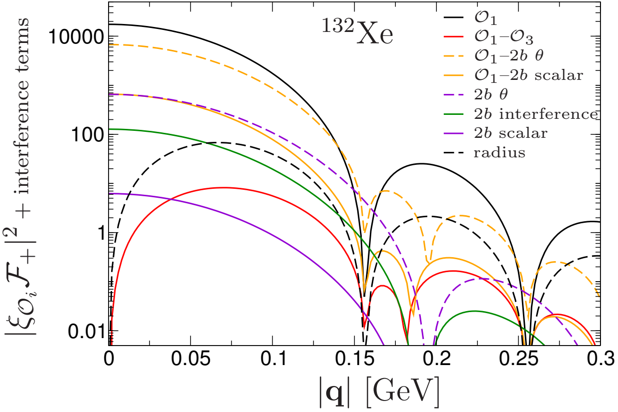
2b scalar currents also explored by

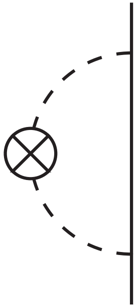
Cirigliano et al.
JHEP10 25(2012)
PLB739 293(2014)

2b structure factors numerically large, especially 2b θ (gluonic coupling)
However, estimated correction to leading 1b terms $\lesssim$ 10% in simple models:
scalar interactions (no *s* quark) / purely gluonic couplings

Radius corrections

Hadronic radius corrections (q^2 corrections) to the $\mathcal{O}_1$ operator also coherent





Vanishing at $q = 0$, for finite q values comparable to 2b terms, in agreement with chiral EFT (both third-order corrections)

Generalized SI cross-section

General WIMP-nucleus scattering cross-section: 8 contributions
isovector counterpart of $\mathcal{O}_1$, scalar and θ-term 2b currents
radius corrections to $\mathcal{O}_1$, nucleon spin-orbit $\mathcal{O}_3$ operator (isoscalar+isovector)

$$\frac{d\sigma^{\mathrm{SI}}_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{1}{4\pi\mathbf{v}^2}\bigg|\left(c_+^M - \frac{\mathbf{q}^2}{m_N^2}\,\dot{c}_+^M\right)\mathcal{F}_+^M(\mathbf{q}^2) + c_\pi\mathcal{F}_\pi(\mathbf{q}^2) + c_\pi^\theta\mathcal{F}_\pi^\theta(\mathbf{q}^2) + \left(c_-^M - \frac{\mathbf{q}^2}{m_N^2}\,\dot{c}_-^M\right)\mathcal{F}_-^M(\mathbf{q}^2) + \frac{\mathbf{q}^2}{2m_N^2}\left[c_+^{\Phi''}\mathcal{F}_+^{\Phi''}(\mathbf{q}^2) + c_-^{\Phi''}\mathcal{F}_-^{\Phi''}(\mathbf{q}^2)\right]\bigg|^2,$$

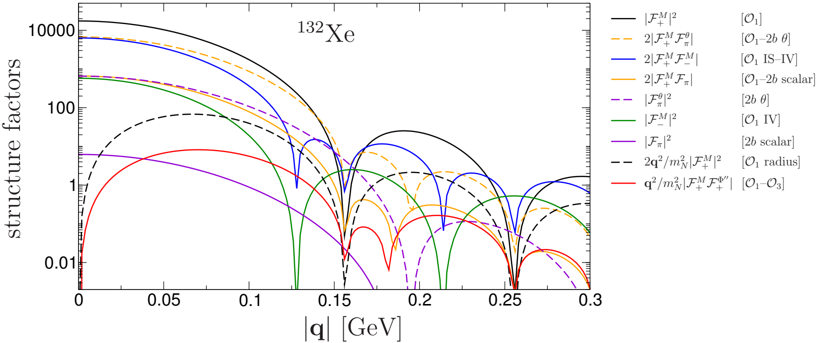
Ideally, correlated analysis considering several nuclear targets

Parameters c not all independent:
Only 7/4 independent Wilson coefficients for Dirac/Majorana spin-$1/2$ WIMPs
C_q^{SS}, $C_g^{\prime S}$, C_q^{VV} $(q = u, d, s)$, no C_q^{VV}'s in Majorana case

Minimal extension of SI analyses

The hierarchy in structure factors allows to propose a minimal extension:

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



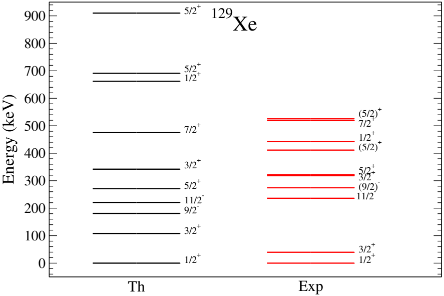
Strategy for analyzing single experiment: one-operator-at-a-time

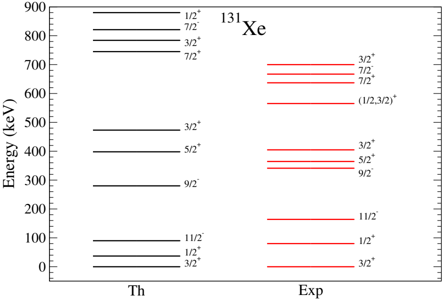
Set limits on each c-coefficient (setting other $c_i = 0$)

Constrain 4 different combinations of new-physics parameters (not only c_+)

Inelastic scattering?

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





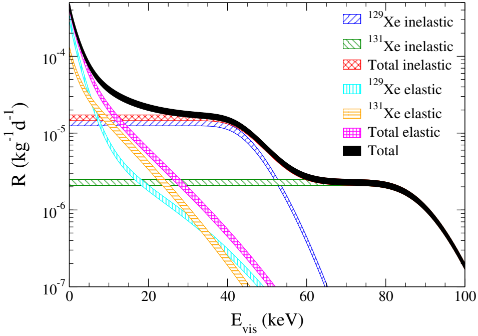
Very low-lying first-excited states $\sim 40, 80$ keV

If WIMPs have enough kinetic energy
inelastic scattering possible

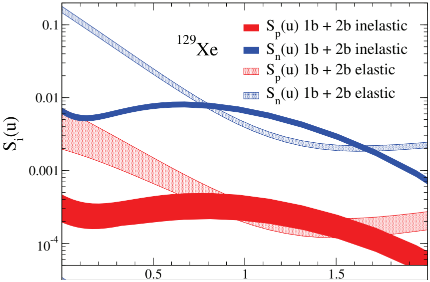
$$p_{\pm} = \mu v_i \left(1 \pm \sqrt{1 - \frac{2E^*}{\mu v_i^2}} \right)$$

Spin-dependent inelastic WIMP scattering

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



Baudis et al. PRD88 115014 (2013)



Inelastic scattering ⇒ spin coupling
SI inelastic suppressed:
coherence of all nucleons always lost

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

One plateau per excited state

Even if suppressed, obserbable if XENON1T finds signal
McCabe JCAP05 (2016) 033

Summary

Nuclear structure aspects:
coherence, WIMP couplings to two-nucleons, inelastic scattering
very important for fully exploiting direct dark matter detection experiments

SD scattering:
2b currents (axial-axial)
entangle protons and neutrons
impact xenon "proton" response

SI (coherent) scattering:
Isovector counterpart of usual SI term
2b currents (scalar and θ coupling)
Each term constrains different new physics

Inelastic scattering:
can be detected in xenon,
non-coherent interaction

Nuclear structure outlook:
Ab-initio based calculations
with controlled uncertainties