Matrix Elements for Fundamental Symmetries

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Collaborators

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- IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG — E.Caurier, F. Nowacki

Outline

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Why testing Fundamental Symmetries with Nuclei?

Nuclear Structure calculations

Derivation of Hadronic Currents: chiral EFT

Nature of Neutrinos and Lepton-number Violation:
Neutrinoless Double-Beta Decay

Search for Supersymmetric Dark Matter Particles:
WIMP Scattering off Nuclei

Summary

Symmetries in Physics

Symmetries play a crucial role in our understanding of Nature

They can lead to conservation laws:

- Translational symmetry ⇒ Energy-Momentum conservation
- Rotational symmetry ⇒ Angular Momentum conservation

They explain properties of particles:

- Chiral symmetry of QCD ⇒ Pions are much lighter than other mesons

Some symmetries predict allowed processes (unless violated)

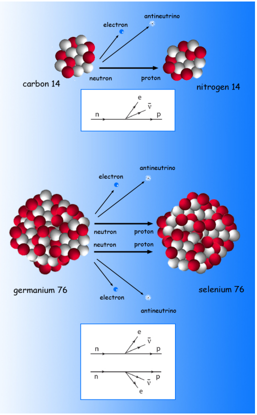
- Lepton number (L), Baryon number (B), CPT...

And there is new symmetries that have been proposed:

- Supersymmetry...

Lepton-Number (L) conservation

Lepton number conserved in
all processes observed so far:



β decay, $\beta\beta$ decay...

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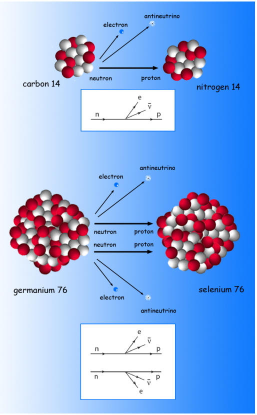
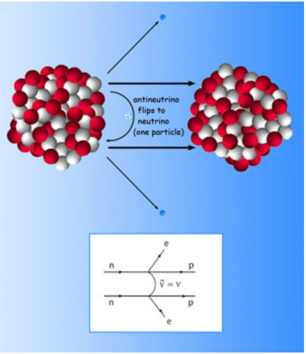


β decay, $\beta\beta$ decay...

Uncharged massive particles like Majorana neutrinos (ν) theoretically allow L violation



Neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay

Supersymmetry (SUSY)

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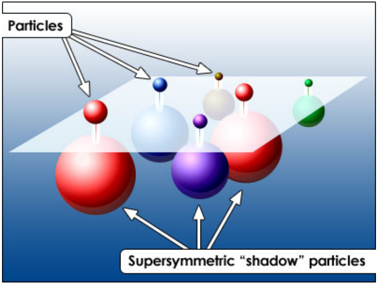
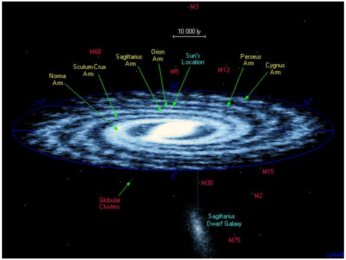
Supersymmetry
(supersymmetric partners for the fundamental particles we know) introduced in extensions of the Standard Model of particle physics

They solve purely theoretical problems (gauge hierarchy)



Supersymmetric particles
promising candidates
for Dark Matter of our Universe

They would naturally occur in observed Dark Matter densities



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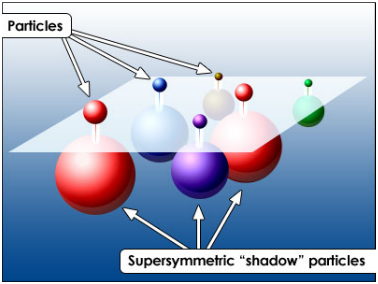
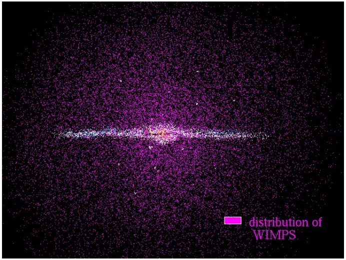




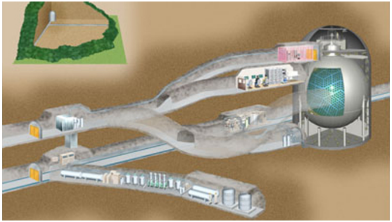
Testing Symmetries with Nuclei

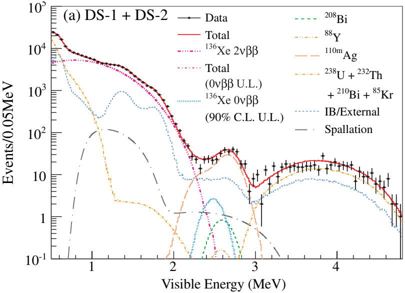
Symmetries can be test in particle accelerators (LHC)

Experiments with nuclei offer an alternative:
Nuclei are abundant in huge numbers $N_A = 6.02\ 10^{23}$ nuclei in A grams!
Lots of material over long times allow to:

- Detect L-violating processes with very small branching ratios
- Measure SUSY-baryon cross-sections even if interactions are weak

Isolate from other processes:
very low background (underground)





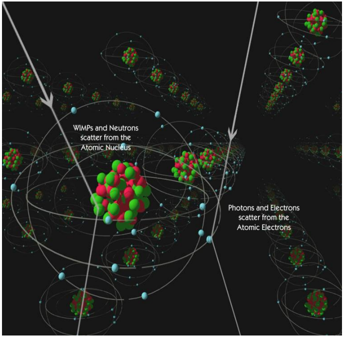
KamLAND-Zen, PRL110 062502 (2013)

Matrix Elements for Fundamental Symmetries

To study Fundamental Symmetries we need Nuclear Matrix Elements

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

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



CDMS Collaboration

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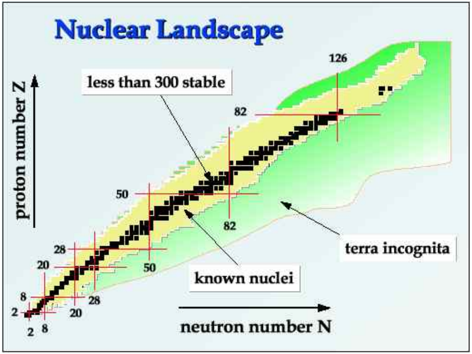
Nuclear Structure approach



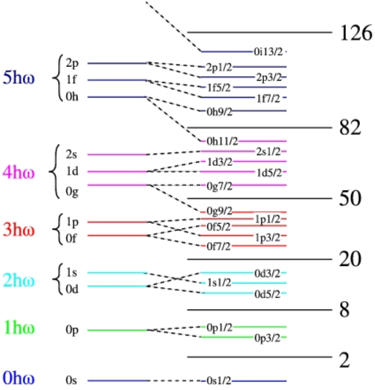
Big variety of nuclei in the nuclear chart, $A \sim 2...300$

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

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

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

The Interacting Shell Model



Chose as basis states that of the 3D Harmonic Oscillator

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

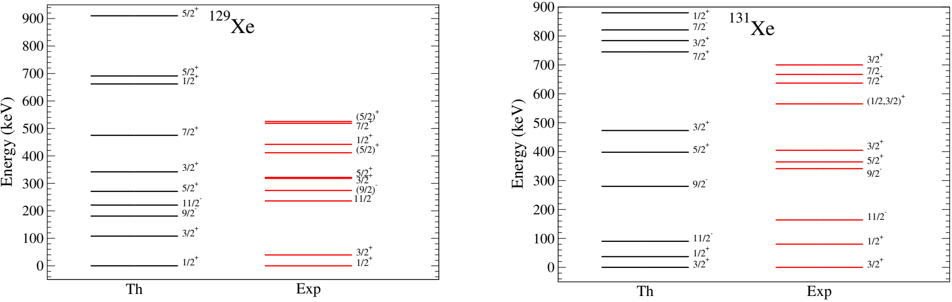
- Inner core: orbits that are always filled
- Valence space: the space in which we explicitly solve the problem
- Outer space: orbits that are always empty

Solve in valence space: $H|\Psi\rangle = E|\Psi\rangle \rightarrow H_{eff}|\Psi\rangle_{eff} = E|\Psi\rangle_{eff}$

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

^{129,131}Xe spectra

The agreement with experimental spectra is very good!



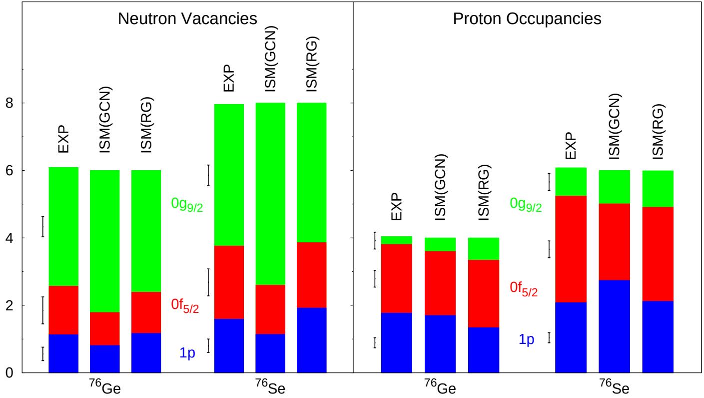
JM, Gazit, Schwenk PRD86 103511(2012)

Note that show first 10 states out of total $\sim 10^8$

No information about these particular nuclei present in the calculation

Occupancies of ^{76}Ge, ^{76}Se

Experimental occupancies are well described!



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

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

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Forces and Currents in Chiral EFT

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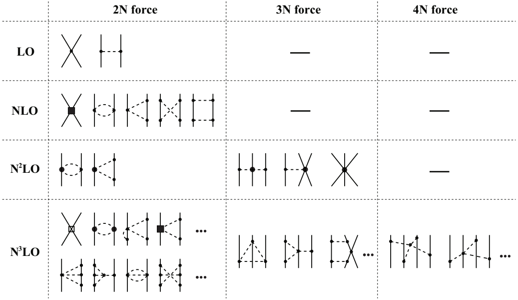
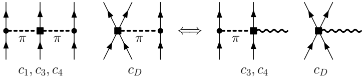
Chiral EFT: low energy approach to QCD for nuclear structure energies

Approximate chiral symmetry of QCD: pions pseudo-Goldstone bosons

Short-range couplings are fitted to experiment once

Systematic expansion: nuclear forces and electroweak currents





Same NN and 3N couplings

Park et al. PRC67 055206(2003)

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

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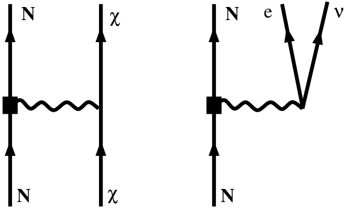
Hadronic currents in chiral EFT

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

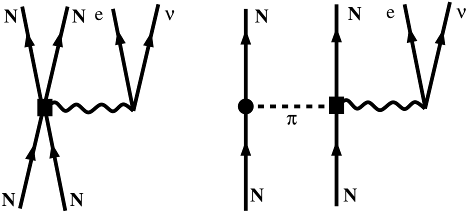
Same expressions obtained using phenomenological arguments



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

Reflect interactions between nuclei

Long-range currents dominant
Relevant momentum transfers $\sim m_\pi$



Two-body currents in light nuclei

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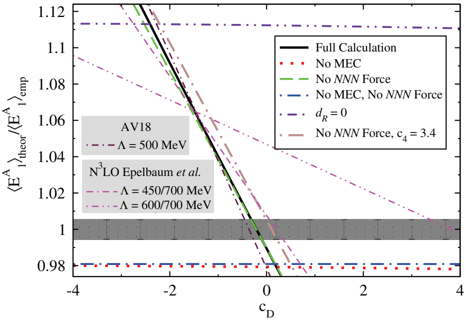
Two-body currents needed to reproduce data in light nuclei:

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

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

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

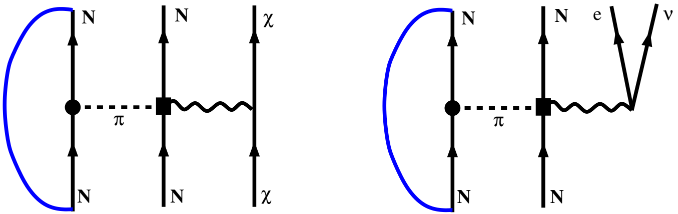


2b current contributions $\sim$ few % in light nuclei ($Q \sim \sqrt{BEm}$)
2b currents order Q^3 $\Rightarrow$ larger effect in medium-mass nuclei ($Q \sim k_F$)

Normal-ordered 2b currents

Approximate 2b currents in medium-mass nuclei taking normal-ordered 1-body approximation with respect to Fermi gas,

Sum over one nucleon, direct and the exchange terms



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

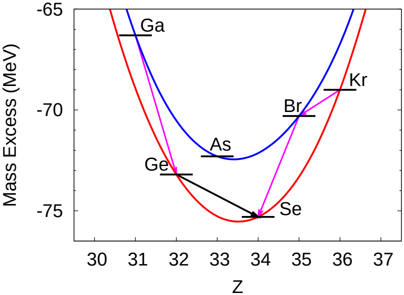
$\mathbf{J}^{\text{eff}}_{n,2b}$ depends on chiral EFT couplings c_3, c_4
known, with uncertainties, from nuclear force studies

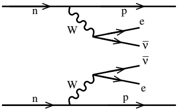
Corrections are $\sim (n_{\text{valence}}/n_{\text{core}})$ in Fermi systems

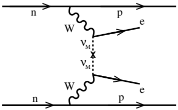
Outline

Neutrinoless Double beta decay

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







$T^{2\nu\beta\beta}_{1/2} \gtrsim 10^{19}$ y $\quad T^{0\nu\beta\beta}_{1/2} > 10^{25}$ y

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

Only candidates with $Q_{\beta\beta} > 2$ MeV experimentally interesting for $0\nu\beta\beta$ decay (very slow process)

Nuclear Matrix Elements (NMEs)

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

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

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

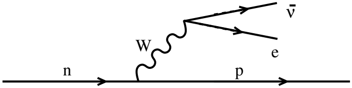
$$M^{0\nu\beta\beta} = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_X H^X(r)\,\Omega^X |0_i^+\rangle$$

- Many-body method to describe initial and final nuclear states (ISM)
- Transition operator, appropriate for this decay (chiral EFT)

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

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

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



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

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

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

This puzzle has been the target of many theoretical efforts:

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

Revisit in the framework of (chiral EFT) currents

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

Contribution of 2b currents

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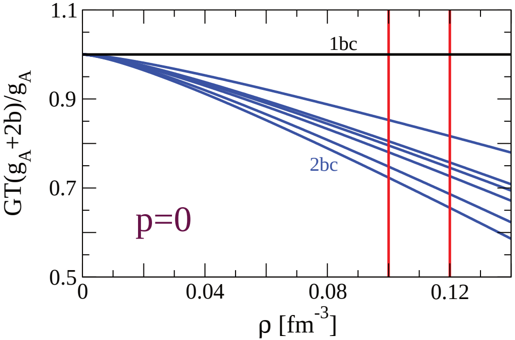
The normal-ordered two-body currents modify GT operator

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

p dependent   long-range



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

Couplings c_3, c_4 from NN potentials

Entem et al. PRC68 041001(2003)

Epelbaum et al. NPA747 362(2005)

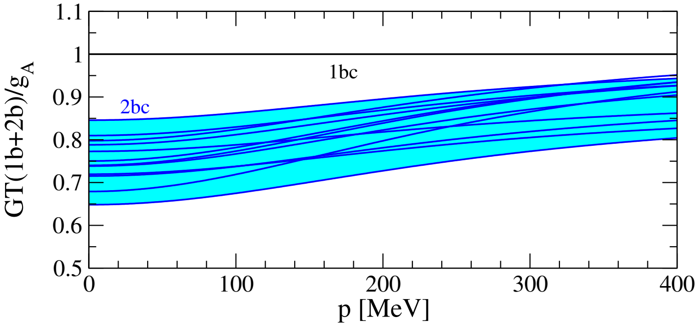
Rentmeester et al. PRC67 044001(2003)

$\delta c_3 = -\delta c_4 \approx 1 \text{ GeV}^{-1}$

2b currents predict g_A quenching
$q = 0.85 \ldots 0.66$

Transferred-momentum dependence

The $\sigma\tau^-$ term depends on transferred momentum p: $\frac{2}{3}\, c_3\, \frac{\mathbf{p}^2}{4m_\pi^2+\mathbf{p}^2}$

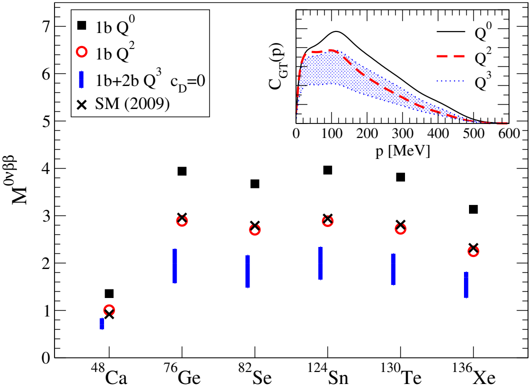


JM, Gazit, Schwenk PRL107 062501 (2011)

Quenching gets weaker at $p > 0$

Typically $p \sim 100$ MeV $\sim m_\pi$ for $0\nu\beta\beta$ decay

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



JM, Gazit, Schwenk PRL107 062501 (2011)

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

Order Q^0+Q^2 similar to calculations with phenomenological currents
JM, Poves, Caurier, Nowacki
NPA818 139 (2009)

At order Q^3 2b currents reduce $\sim$ 35% the NME

Smaller than -45% ($q^2 = 0.74^2$) due to momentum-transfer $p > 0$

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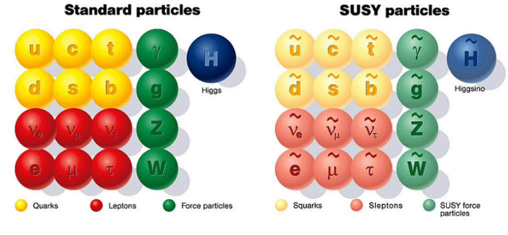
SUSY, WIMPs and Dark Matter

Supersymmetric particles proposed in extensions of the Standard Model include Weakly Interacting Massive Particles (WIMPs)

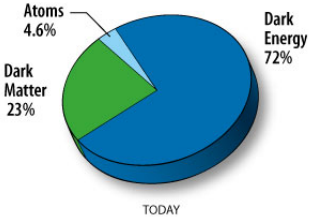


WIMPs are Dark Matter candidates

DM challenge: we know it is there, we don't know of what it consists

Evidence for DM strong but indirect: rotation curves, lensing...

Motivates DM direct searches



Spin-Dependent WIMP scattering off nuclei

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Spin-Dependent elastic WIMP scattering off nuclei ⇒ odd-A nuclei

The cross-section is governed by the Structure factor $S(p)$

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

$$\mathbf{S}(\mathbf{p}) = \sum_L\left(\left|\langle J_f||\mathcal{E}_L(p)||J_i\rangle\right|^2 + \left|\langle J_f||\mathcal{L}_L(p)||J_i\rangle\right|^2\right),$$ Trans. Electric+Longitudinal multipoles

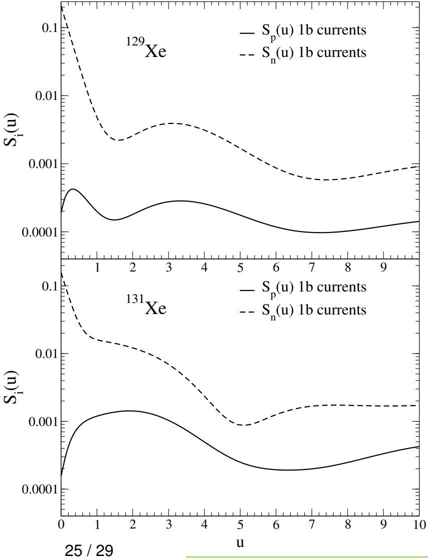
$$\mathcal{E}_L(p) = \frac{1}{\sqrt{2L+1}}\sum_{i=1}^{A}\frac{1}{2}\left[a_0 + a_1\tau_i^3\left(1-2\frac{p^2}{\Lambda_A^2}+\delta a_1\right)\right] \qquad \delta a_1 < 0$$

$$\times\left[-\sqrt{L}M_{L,L+1}(p\mathbf{r}_i)+\sqrt{L+1}M_{L,L-1}(p\mathbf{r}_i)\right] \qquad \delta a_1^P(p) > 0$$

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

$$\times\left[\sqrt{L+1}\,M_{L,L+1}(p\mathbf{r}_i)+\sqrt{L}M_{L,L-1}(p\mathbf{r}_i)\right], \text{with } M_{L,L'}(p\mathbf{r}_i) = j_{L'}(pr_i)[Y_{L'}(\hat{\mathbf{r}}_i)\,\sigma_i]^L.$$

Structure factors with 1b currents



Isoscalar and isovector WIMP-nucleus couplings shape Structure factor

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

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

$$S(0) = \frac{(2J+1)(J+1)}{\pi J} \left| \frac{a_0+a_1}{2} \langle S_p \rangle + \frac{a_0-a_1}{2} \langle S_n \rangle \right|^2$$

'Neutron'/'Proton' couplings

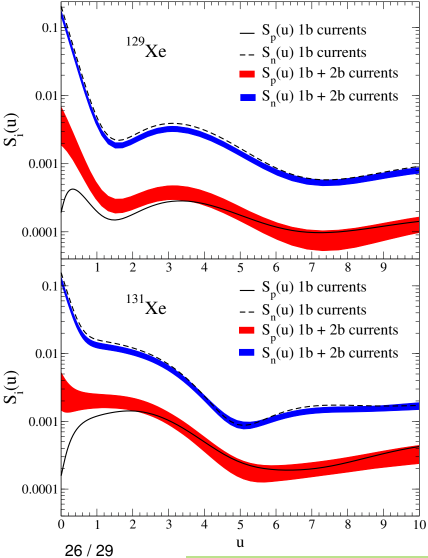
$a_1 = -a_0 / a_1 = a_0$ maximize/minimize S:

$S_n \propto \left|\langle S_n \rangle\right|^2$ and $S_p \propto \left|\langle S_p \rangle\right|^2$

Distinction no longer holds at $p > 0$: peak in $S_p(u)$, with $u = p^2 b^2 / 2$

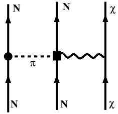
Klos, JM, Gazit, Schwenk, to be submitted

Structure factors with 1b+2b currents



2b currents allow, in the $a_1 = a_0$ case, neutrons to contribute at $p = 0$

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



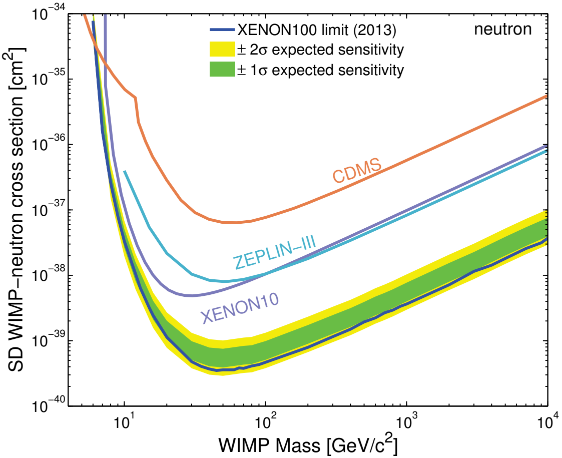
increase dramatically $S_p(u)$

S_n reduced by 10-30% at $u \sim 1$ due to a_1 2b correction

S_n possibly enhanced at $u \gtrsim 3$ due to $a_1^P(p)$ 2b term

Details depend on relative contributions from Trans. Electric/Longitudinal

Application to experiment

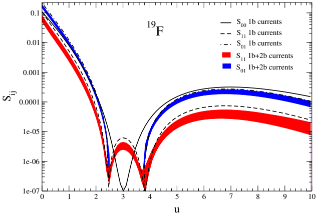


Our calculations used by XENON100 Collaboration to set limits on WIMP-nucleus cross-sections (CS)

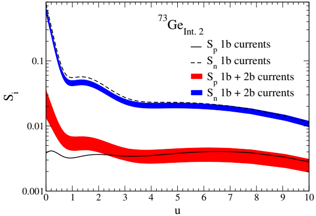
XENON100 obtained world best limits (CS above limit excluded) for Spin-Dependent scattering with 'neutron' couplings

Aprile et al. arXiv:1301.6620

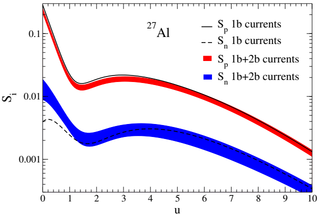
^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge, ^{127}I



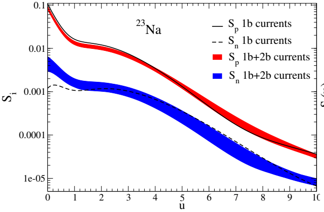
PICASSO, COUPP, SIMPLE



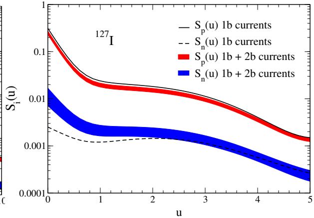
CDMS, EDELWEISS, EURECA



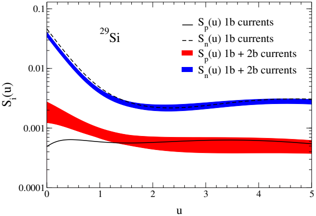
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



CDMS-II

Outline

Why testing Fundamental Symmetries with Nuclei?

Nuclear Structure calculations

Derivation of Hadronic Currents: chiral EFT

Nature of Neutrinos and Lepton-number Violation:
Neutrinoless Double-Beta Decay

Search for Supersymmetric Dark Matter Particles:
WIMP Scattering off Nuclei

Summary

Summary

Nuclei ideal to test Fundamental Symmetries: large masses, long times

Matrix Elements key to design experiments and interpret findings

State-of-the-art nuclear structure calculations using ISM:
good spectroscopic description

Chiral EFT provides hadronic currents including 2b currents

Matrix Elements for Neutrinoless $\beta\beta$ decay for several candidates

- 2b currents reduce (quench) Matrix Elements in 35%
- *p*-dependence of GT reduction predicted

Structure factors for Spin-Dependent elastic WIMP scattering off nuclei
for experimentally relevant nuclei

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