Nuclear Matrix Elements for Fundamental Symmetries

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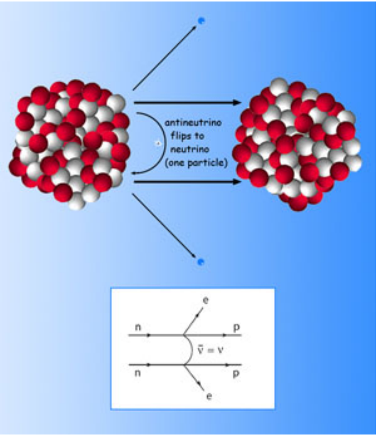
東京大学
THE UNIVERSITY OF TOKYO

Neutrinoless $\beta\beta$ decay, Dark Matter detection

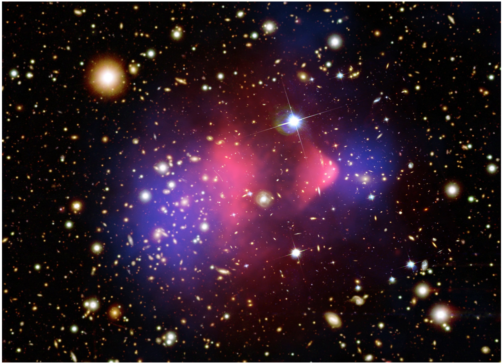
Neutrinoless double-beta decay

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



Dark matter scattering off nuclei

What is Dark Matter made of?



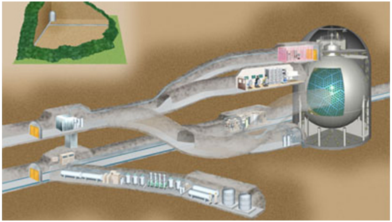
Nuclear physics and fundamental symmetries

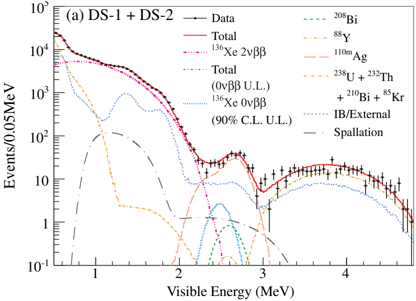
Neutrinos, Dark Matter can be studied with high-energy experiments

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

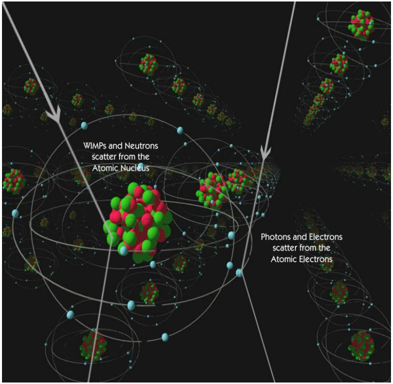
Nuclear matrix elements

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...

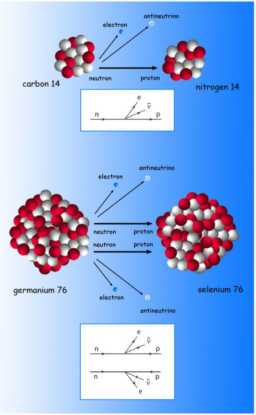
- Lepton-nucleus interaction: Evaluate (non-perturbative) hadronic currents inside nucleus: phenomenology, effective theory



CDMS Collaboration

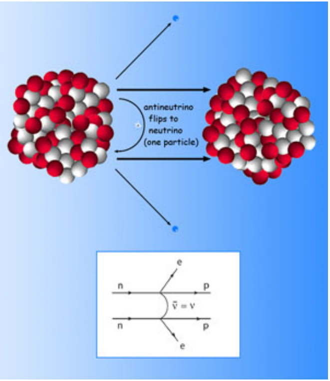
Lepton-number conservation

Lepton number conserved
in all processes observed to date



β decay, $2\nu\beta\beta$ decay...

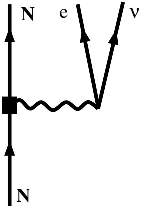
Uncharged massive particles
like Majorana neutrinos ($\nu = \bar{\nu}$)
theoretically allow lepton number violation



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

Weak transitions in nuclei

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

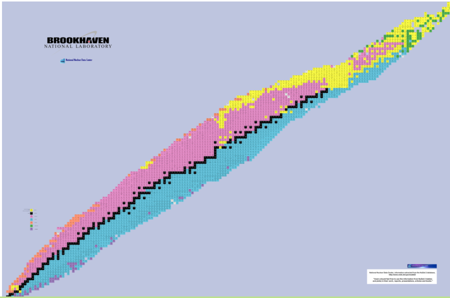
Standard Model: $J_L^{\mu\dagger}$ for quarks, need $J_L^{\mu\dagger}$ for nucleons

In nuclei (non-relativistic), β decay is

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

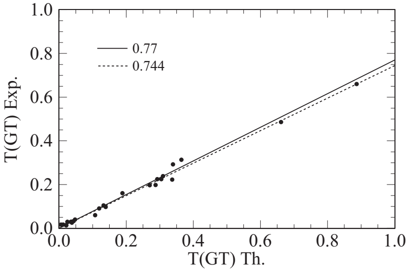
Fermi and Gamow-Teller transitions

corrections (forbidden transitions)
expansion of the lepton current



Gamow-Teller transitions

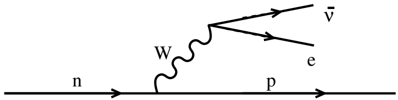
Single-β, $2\nu\beta\beta$ decays well described by nuclear structure: shell model...



Martinez-Pinedo et al. PRC53 2602(1996)

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

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



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

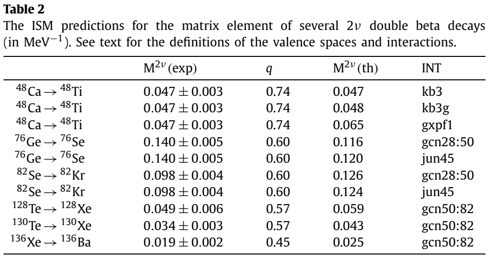


Table 2

The ISM predictions for the matrix element of several 2ν double beta decays (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

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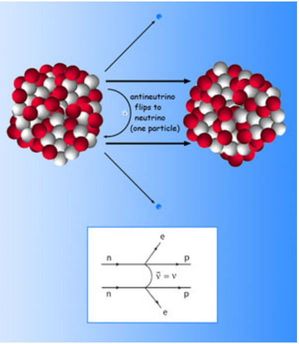
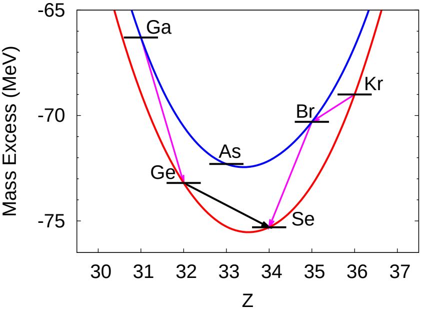
Caurier, Nowacki, Poves PLB711 62(2012)

Neutrinoless double-beta decay

Neutrinoless double-beta decay ($0\nu\beta\beta$):
Lepton-number violation, Majorana nature of neutrinos

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

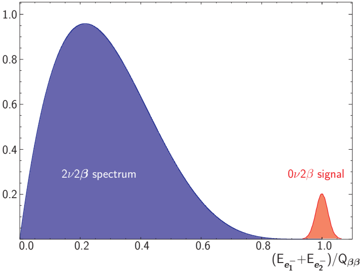


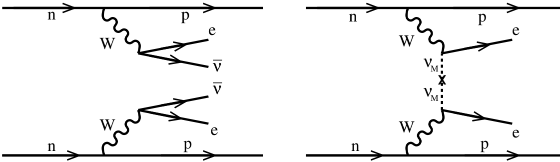


$^{48}\text{Ca} \to {}^{48}\text{Ti}$
$^{76}\text{Ge} \to {}^{76}\text{Se}$
$^{82}\text{Se} \to {}^{82}\text{Kr}$
$^{96}\text{Zr} \to {}^{96}\text{Mo}$
$^{100}\text{Mo} \to {}^{100}\text{Ru}$
$^{110}\text{Pd} \to {}^{110}\text{Cd}$
$^{116}\text{Cd} \to {}^{116}\text{Sn}$
$^{124}\text{Sn} \to {}^{124}\text{Te}$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

$\beta\beta$ decays

$\beta\beta$ decays are quite different processes





$$2\nu\beta\beta : E_{e_1} + E_{e_2} + E_{\bar{\nu}_1} + E_{\bar{\nu}_2} = Q_{\beta\beta}$$

$$0\nu\beta\beta : E_{e_1} + E_{e_2} = Q_{\beta\beta}$$

In $2\nu\beta\beta$ decay, the momentum transfer limited by $Q_{\beta\beta}$, while for $0\nu\beta\beta$ decay larger momentum transfers are permitted

In $0\nu\beta\beta$ decay the Majorana neutrinos are part of the transition operator,
via the so-called neutrino potential

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

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

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

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

$M^{0\nu\beta\beta}$ is the nuclear matrix element

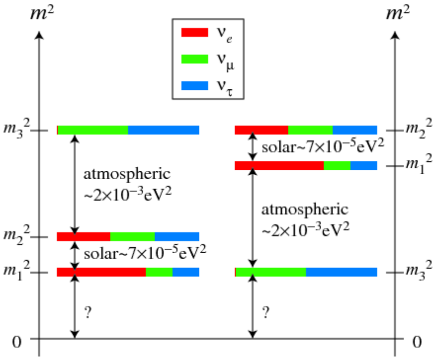
G_{01} is the phase space factor: $Q_{\beta\beta}$, electrons...

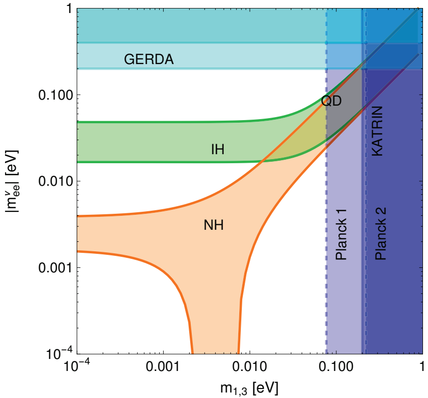
$M^{0\nu\beta\beta}$ is necessary to identify best candidates for experiment, and to obtain neutrino masses, with $m_{\beta\beta} = |\sum U_{ek}^2 m_k|$

Compete with other determinations of neutrino masses:
single-β decay ($\sqrt{\sum |U_{ek}|^2 m_k^2}$) and cosmology ($\sum m_k$)

Neutrino mass hierarchy

Nuclear matrix elements combined with $0\nu\beta\beta$ decay lifetimes can determine the mass hierarchy of neutrinos

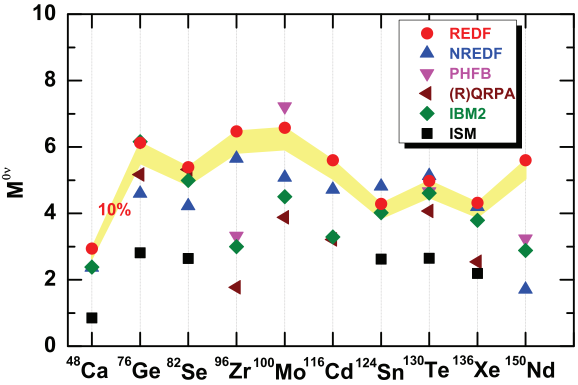




Neutrino mass differences known from neutrino oscillation experiments

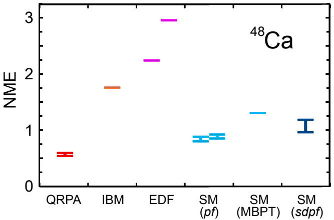
Neutrinoless $\beta\beta$ decay matrix elements

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?

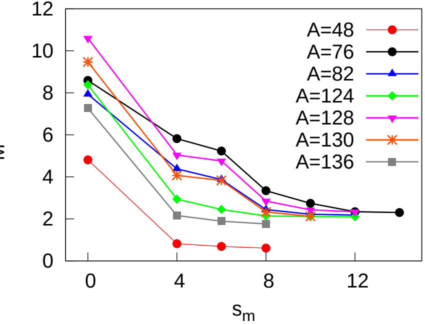


Shell model small matrix elements:
What is the effect of the small valence space?

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

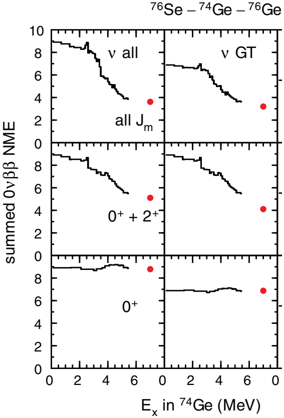
$0\nu\beta\beta$ decay is favoured by pairing correlations

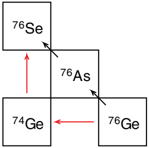
Maximum between superfluid nuclei, reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Related to two-nucleon transfers



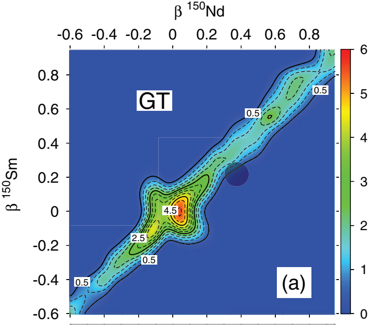


Brown et al. PRL113 262501 (2014)

Deformation and $0\nu\beta\beta$ decay

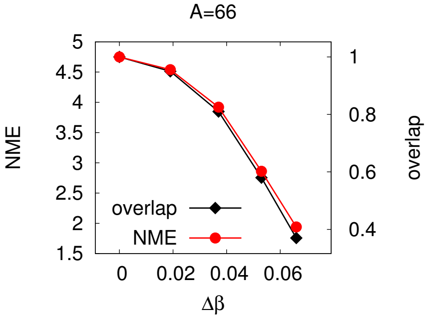
$0\nu\beta\beta$ decay is disfavoured by quadrupole correlations

$0\nu\beta\beta$ decay very suppressed when nuclei have different structure



Rodríguez, Martínez-Pinedo

PRL105 252503 (2010)



JM, Caurier, Nowacki, Poves

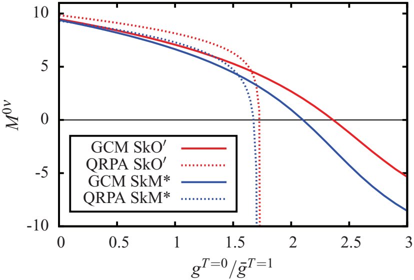
JPCS267 012058 (2011)

Suppression also observed with QRPA Fang et al. PRC83 034320 (2011)

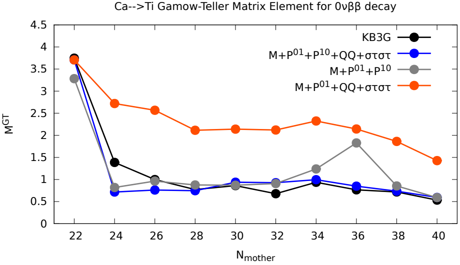
Proton-neutron pairing and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay very sensitive to proton-neutron (isoscalar) pairing

Matrix elements too large if proton-neutron correlations are neglected



Hinohara, Engel PRC90 031301 (2014)



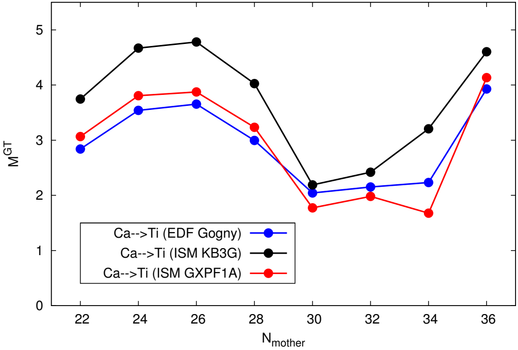
JM, Hinohara, Rodriguez, Engel, Martínez-Pinedo

Related to approximate *SU*(4) symmetry of the $0\nu\beta\beta$ decay operator

$0\nu\beta\beta$ 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

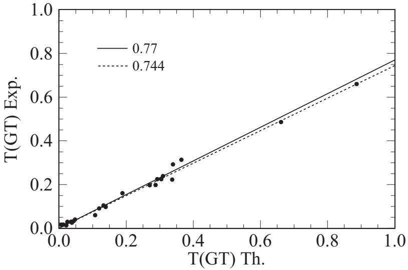
JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)

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)

Gamow-Teller transitions: quenching

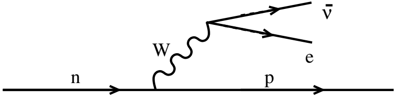
Single-β, 2$\nu\beta\beta$ decays well described by nuclear structure: shell model...



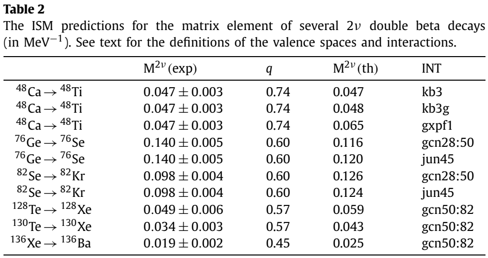
Martinez-Pinedo et al. PRC53 2602(1996)

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

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



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



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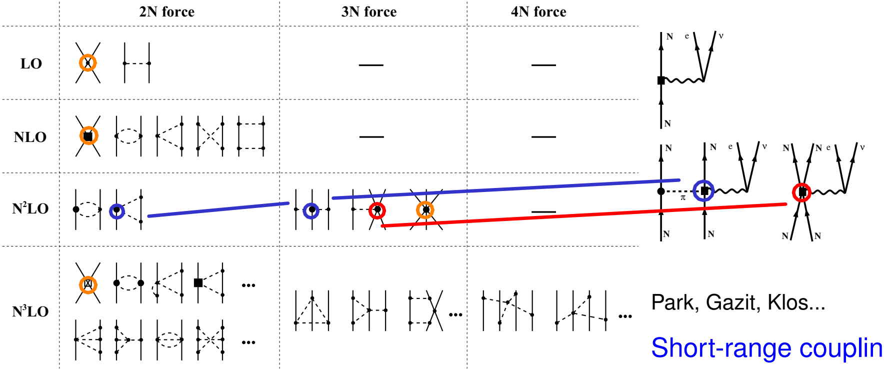
Caurier, Nowacki, Poves PLB711 62(2012)

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



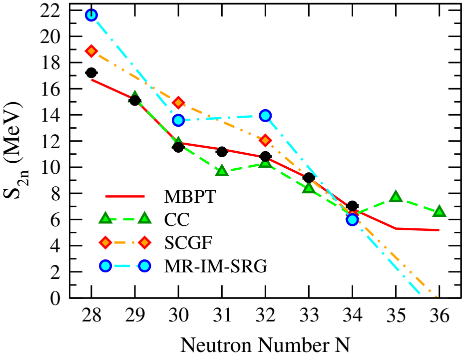
Park, Gazit, Klos...

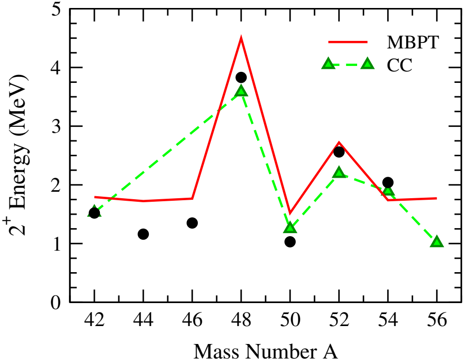
Short-range couplings fitted to experiment once

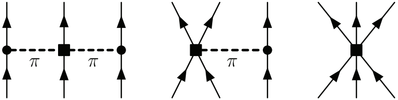
Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...

Calcium isotopes with chiral NN+3N forces

Calculations with NN+3N forces successful in medium-mass nuclei







Prediction of shell closures at ^{52}Ca, ^{54}Ca

^{51,52,53,54}Ca masses [TRIUMF/ISOLDE]

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

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

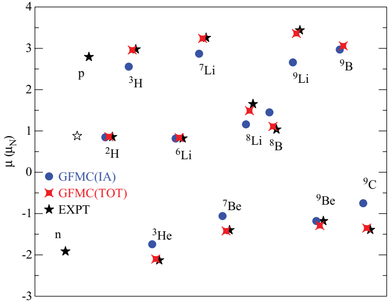
^{8}Be EM transitions

Pastore et al. PRC87 035503(2013)

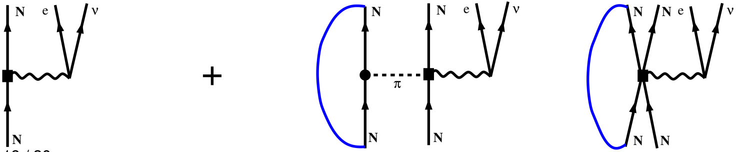
Pastore et al. PRC90 024321(2014)

^{3}H μ capture

Marcucci et al. PRC83 014002(2011)



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

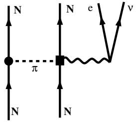


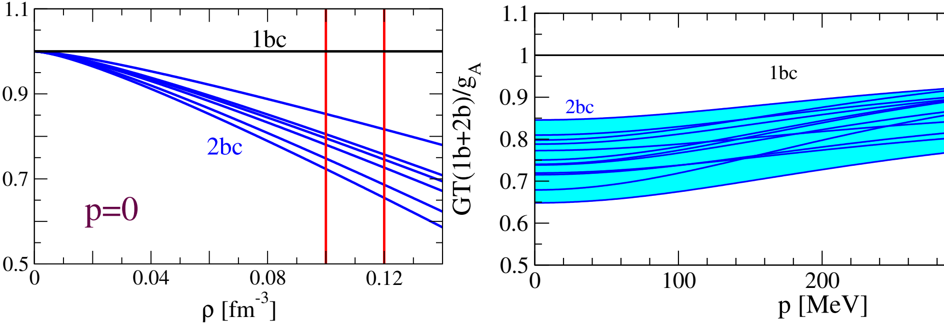
2b currents in medium-mass nuclei

Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

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

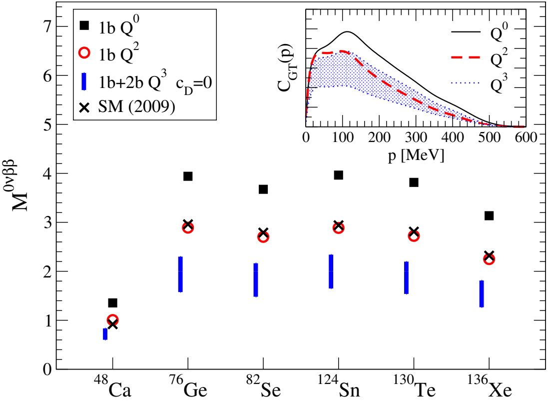




2b currents predict g_A quenching $q = 0.85 \ldots 0.66$

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

Nuclear matrix elements with 1b+2b currents

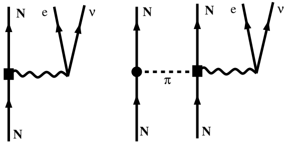


JM, Gazit, Schwenk PRL107 062501 (2011)

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

JM, Poves, Caurier, Nowacki

NPA818 139 (2009)



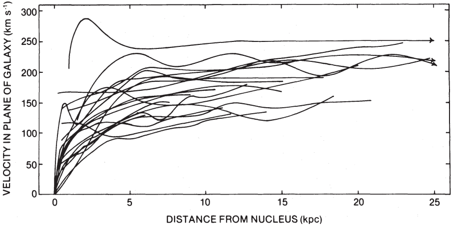
Order Q^3 2b currents reduce NMEs

$\sim 15\% - 40\%$

Coupled-cluster β decay in C, O suggest smaller quenching $q \sim 0.9$

Ekström et al. PRL113 262504 (2014)

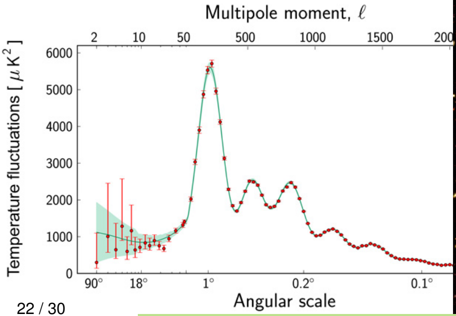
Dark Matter: evidence

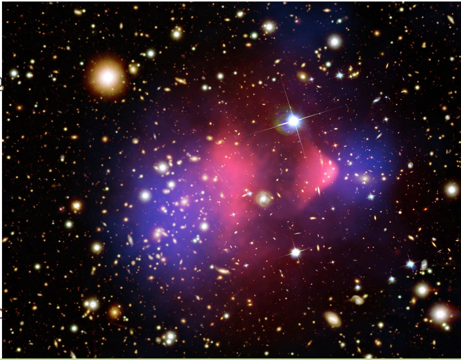


Solid evidence of Dark Matter in very different observations:

Rotation curves, Lensing, CMB...

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

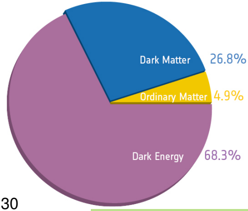




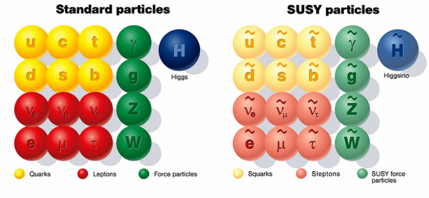
What is Dark Matter made of?

The composition of Dark Matter is unknown
High-energy physics: candidates proposed beyond Standard Model

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

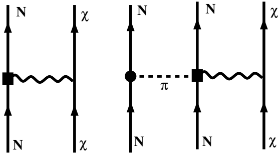


Lightest supersymmetric particles
(usually neutralinos)
predicted in SUSY extensions
of the Standard Model



Expected WIMP-density agrees with observed Dark Matter density

WIMP scattering off nuclei



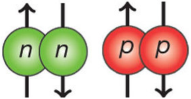
The challenge is direct Dark Matter detection

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

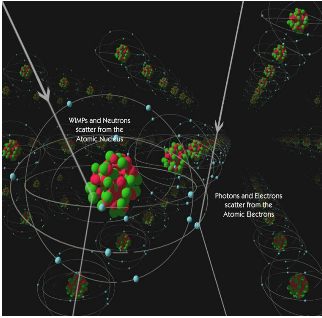
WIMPs couple to the nuclear density

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



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 WIMP-nucleus interaction is

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

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

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

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

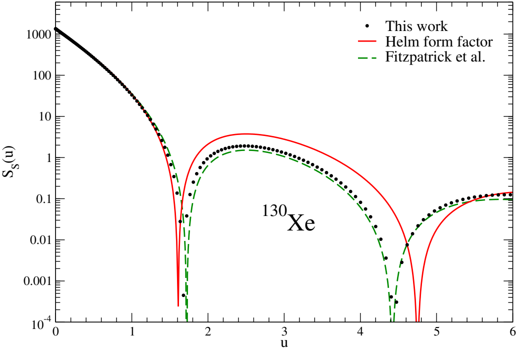
Matrix element of the dark matter scattering: structure factor

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

Spin-independent structure factor for ^{130}Xe

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

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

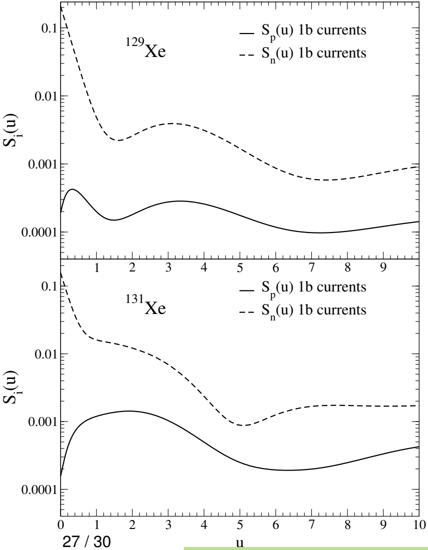


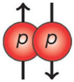
Plot as function of dimensionless $u = p^2 b^2/2$
b harmonic oscillator length

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

SD Structure Factors with 1b+2b currents



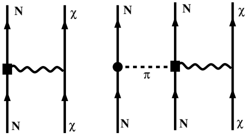


In $^{129,131}_{54}$Xe $\langle S_n \rangle \gg \langle S_p \rangle$,
Neutrons carry most nuclear spin

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

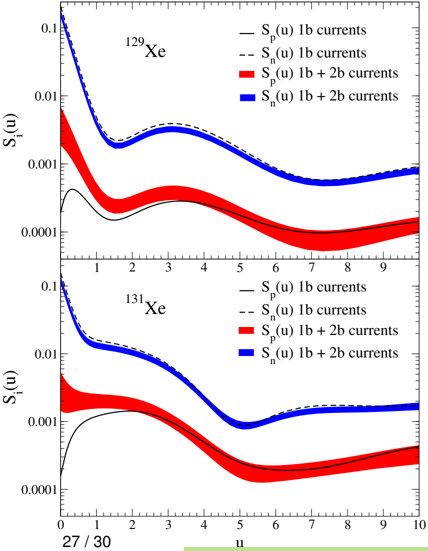
$$S(0) \propto \left| \frac{a_0+a_1}{2} \langle S_p \rangle + \frac{a_0-a_1}{2} \langle S_n \rangle \right|^2$$

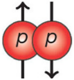
2b currents involve neutrons + protons:



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

SD Structure Factors with 1b+2b currents





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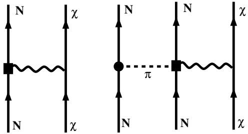
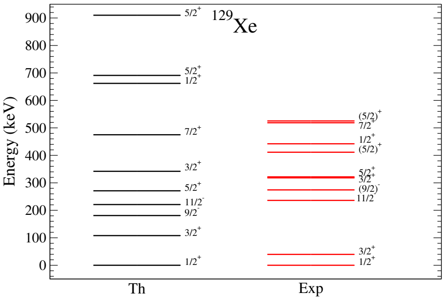
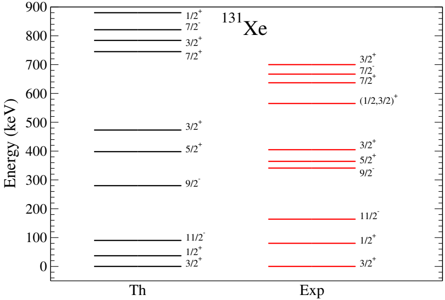


Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

Inelastic scattering?

Can Dark Matter scatter exciting the nucleus to the first excited state?





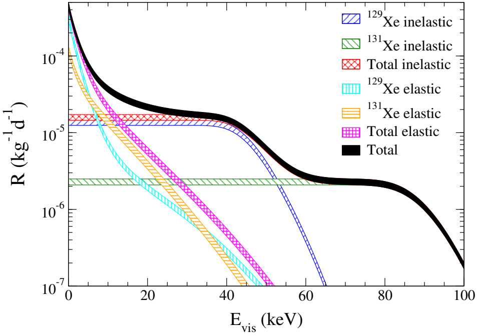
Very low-lying first-excited states $\sim 40, 80$ keV

If WIMPs have enough kinetic energy
inelastic scattering possible

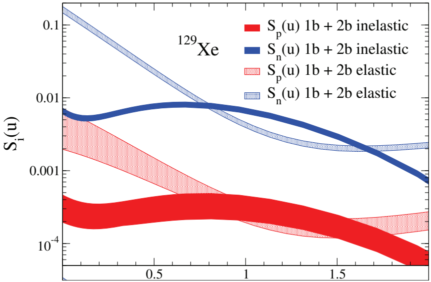
$$p_{\pm} = \mu v_i \left(1 \pm \sqrt{1 - \frac{2E^*}{\mu v_i^2}} \right)$$

Spin-dependent inelastic WIMP scattering

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



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



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

One plateau per excited state

Summary and Outlook

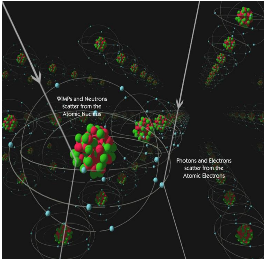
Neutrinoless $\beta\beta$ decay detection will establish the Majorana character of neutrinos and together with nuclear matrix elements inform on neutrino masses

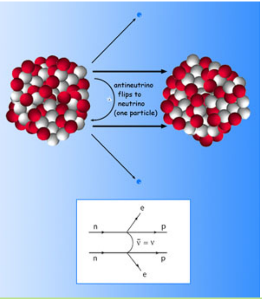
Theoretical nuclear matrix elements disagree: identify relevant correlations and configuration spaces for nuclear structure calculations

Chiral EFT predicts relevant 2b currents that modify the transition operators, need to be better evaluated

Nuclear physics helps Dark Matter searches problems because WIMPs interact with nuclei

Determination of nature and coupling of WIMP-nucleon interaction, more general couplings to be considered





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