Progress in microscopic shell model for medium-mass nuclei and nuclear matrix elements

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

科研費 KAKENHI

Outline

1. Nuclear structure of medium-mass nuclei
2. Matrix elements for $\beta\beta$ decay
3. Dark Matter scattering off nuclei

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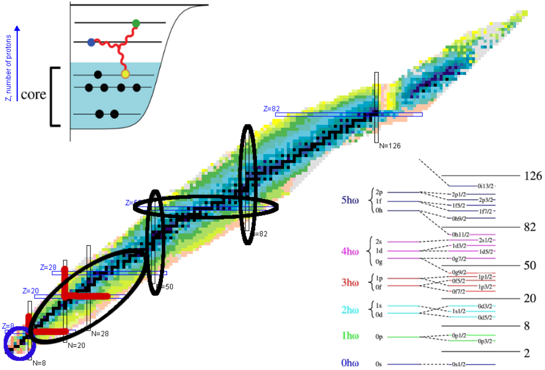
1. Nuclear structure of medium-mass nuclei

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

3. Dark Matter scattering off nuclei

Nuclear landscape



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

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

Hard many-body problem: approximate methods suited for different regions

Shell Model: Choose relevant degrees of freedom (valence space)

Interactions based on realistic nucleon-nucleon (NN) potentials
phenomenological modifications ⇒ three-nucleon (3N) interactions

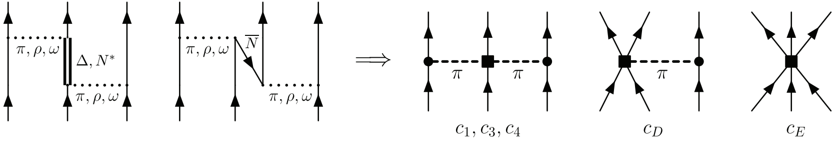
Three-nucleon forces

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

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

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

Bogner, Schwenk, Furnstahl PPNP65 94 (2010)



Difficult to constrain directly

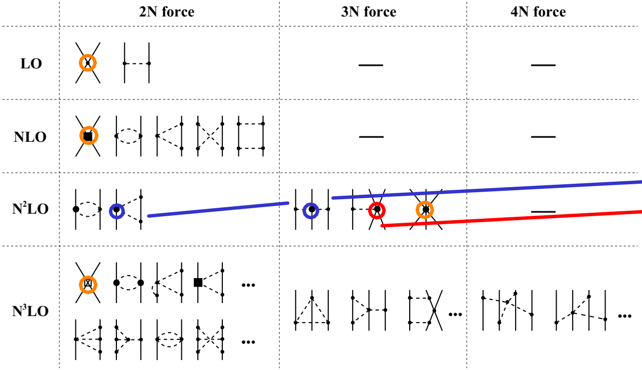
$\Rightarrow$ Chiral EFT, in a natural and systematic manner,
treats 3N forces consistent with NN forces (same for 2b and 1b currents)

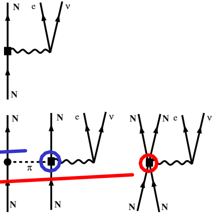
Chiral Effective Field Theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





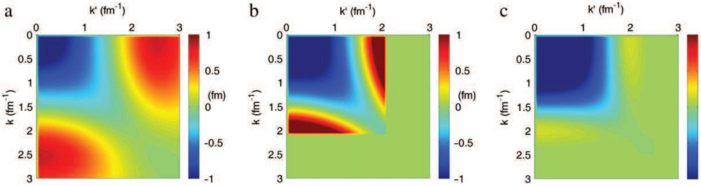
Park et al.
PRC67 055206(2003)

Short-range couplings fitted to experiment once

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

Many Body Perturbation Theory

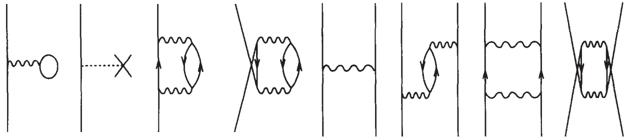
Better convergence of chiral forces after RG transformation



Many-body perturbation theory to third order: obtain effective Shell Model interaction in the valence space

Single Particle Energies

Two-Body Matrix Elements



Effective Hamiltonian in valence space:

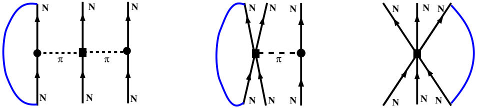
$$H\left|\Psi\right\rangle = E\left|\Psi\right\rangle \rightarrow H_{eff}\left|\Psi\right\rangle_{eff} = E\left|\Psi\right\rangle_{eff}$$

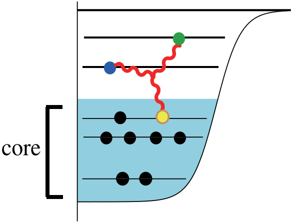
3N couplings c_D, c_E fitted with evolved NN forces (induced + initial 3N forces)

3N Forces: Normal ordering

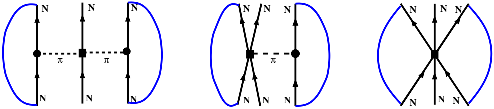
3N forces in normal-ordering approximation:

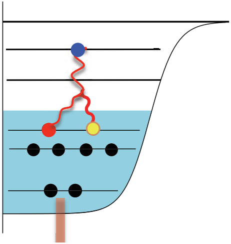
normal-ordered 2B: 2 valence, 1 core particle
⇒ Two-body Matrix Elements





normal-ordered 1B: 1 valence, 2 core particles
⇒ Single particle energies

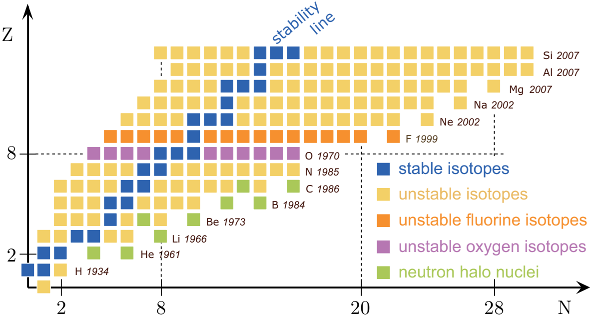


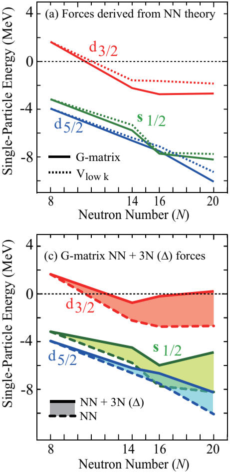


3N forces in $H_{\rm eff}$ treated to third order in MBPT

Oxygen dripline anomaly and 3N forces

O isotopes: 'anomaly' in the dripline at ^{24}O, doubly magic nucleus





Calculations based on chiral NN+3N forces and MBPT correctly predict dripline at ^{24}O

Otsuka et al. PRL105 032501 (2010)

Oxygen dripline in ab-initio calculations

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

No-core shell model (Importance-truncated)

In-medium SRG

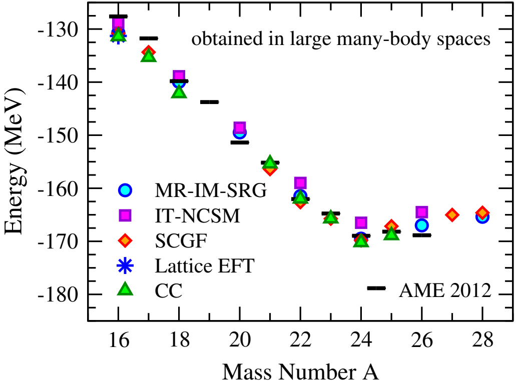
Hergert et al. PRL110 242501 (2013)

Self-consistent Green's function

Cipollone et al. PRL111 062501 (2013)

Coupled-cluster

Jansen et al. PRL113 142502 (2014)



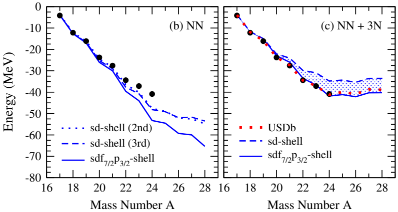
Benchmark with the same initial Hamiltonian

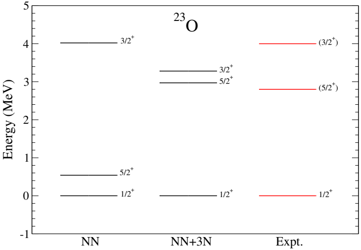
Sensitivity to the chiral interaction not systematically explored

O isotopes: excitation spectra

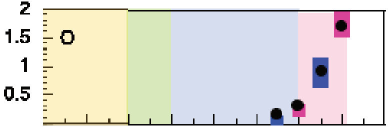
NN+3N calculations good description of excitation spectra

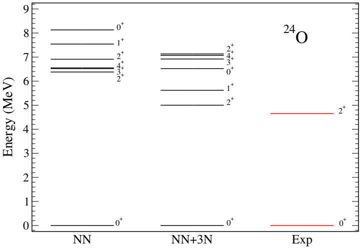
Holt, JM, Schwenk EPJA49 39 (2013)





Spectroscopic factors for $s_{1/2}$ orbital good agreement with experiment, closed ^{24}O





Kanungo et al.

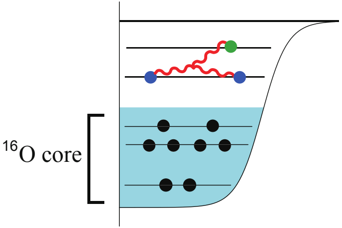
PRL102 152501 (2010); PST152 014002(2013)

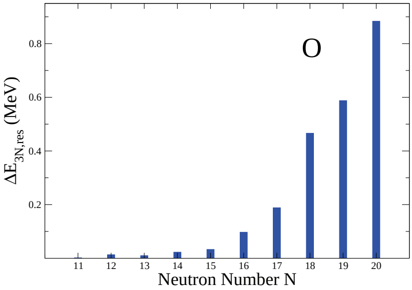
Residual 3N Forces

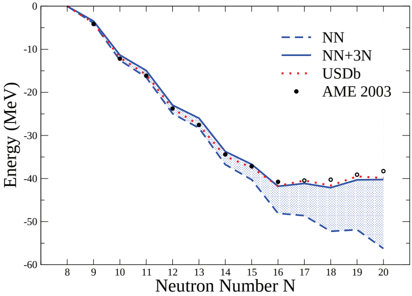
Previous results with normal-ordered 1b and 2b part of 3N forces

In extreme neutron-rich oxygen isotopes, 3N forces between 3 valence neutrons can give a relevant contribution

Evaluated perturbatively: $\langle \Psi | V^{3N} | \Psi \rangle$



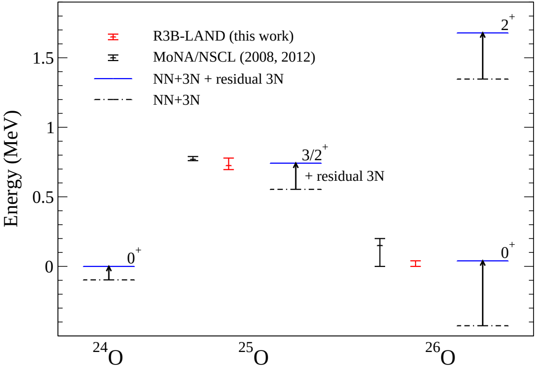




Residual 3N small and repulsive Caesar, Simonis et al. PRC88 034313 (2013)

Beyond the oxygen dripline

Oxygen isotopes beyond the dripline can be accessed with residual 3N forces



Repulsive residual 3N contributions

Small compared to normal-ordered 3N force increase with N

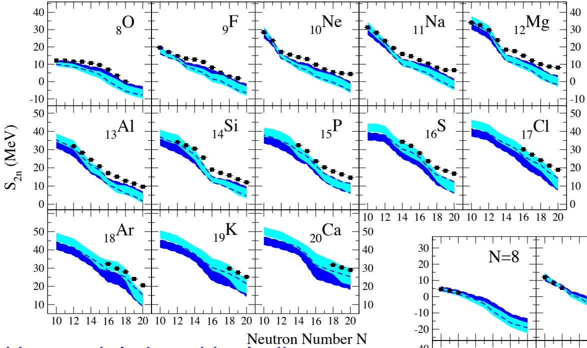
Very good agreement with resonances in ^{25}O and ^{26}O

Caesar, Simonis et al. PRC88 034313 (2013)

Challenge: include continuum degrees of freedom in the calculation

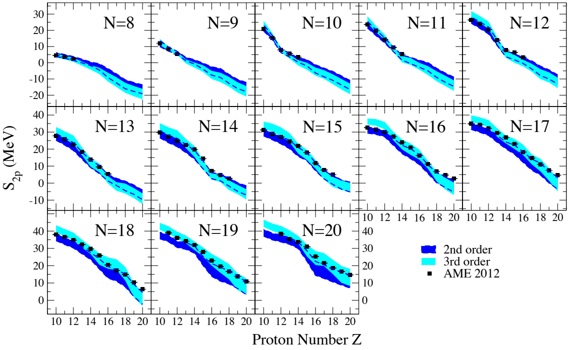
Hagen et al. PRL108 242501 (2012)

Full sd-shell calculation



Full sd-shell calculation with chiral NN+3N forces

Fit only to two, three and four-body systems



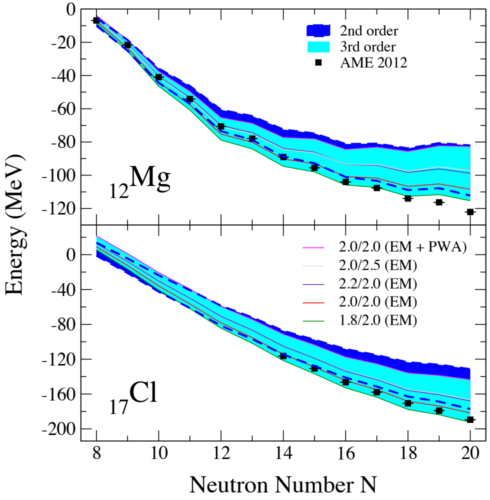
Uncertainly band including different SRG resolution scales and low-energy couplings

Second and third-order MBPT results

Typical uncertainties 5MeV, larger for neutron-rich systems

Nuclei in *sd* shell and theoretical uncertainties

Extend the study to *sd*-shell nuclei, proton-neutron interaction included



Simonis et al. arXiv:1508.05040

Explore the theoretical sensitivity:

Initial chiral Hamiltonian

RG evolution of NN, 3N forces

Convergence in MBPT

Use Hamiltonians with good nuclear saturation properties

Hebeler et al. PRC 83 031301 (2011)

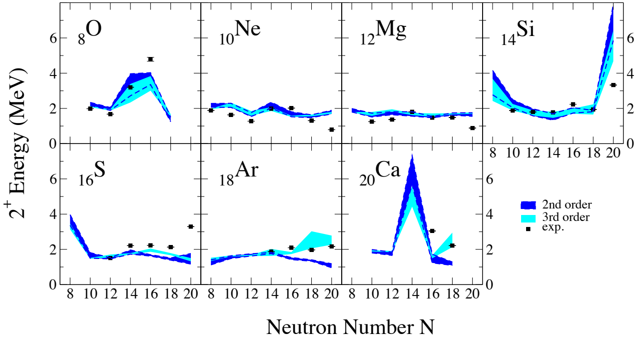
Magnesium ground-state energies underbound, Chlorine good agreement to experiment

Not enough neutron-neutron binding in *sd* shell

Uncertainties dominated by initial nuclear Hamiltonian

2^+ energies in *sd*-shell nuclei

Energies of lowest 2^+ states less sensitive to the initial Hamiltonian



Simonis et al. arXiv:1508.05040

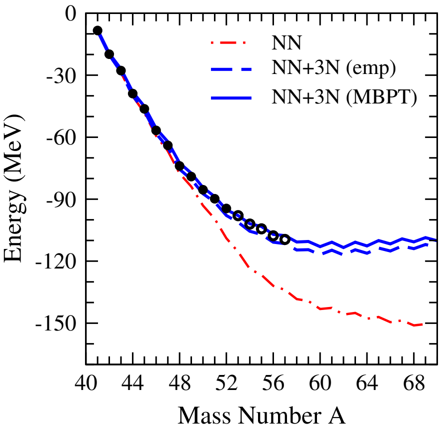
2^+ energies in *sd* shell reasonably well reproduced

Typical uncertainties $\sim$ 500 keV,
MBPT convergence more important in semi-magic nuclei

Island-of-inversion states in Ne, Mg, not reproduced in sd shell calculation

Ca isotopes: masses

Ca isotopes: explore nuclear shell evolution $N = 20, 28, 32?, 34?$



Ca measured from ^{40}Ca core in pf$g_{9/2}$ valence space

3N forces repulsive contribution, chiral NN-only forces too attractive

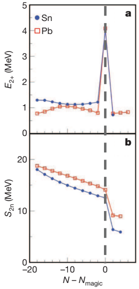
Probe shell evolution:

Mass-differences

2_1^+ energies

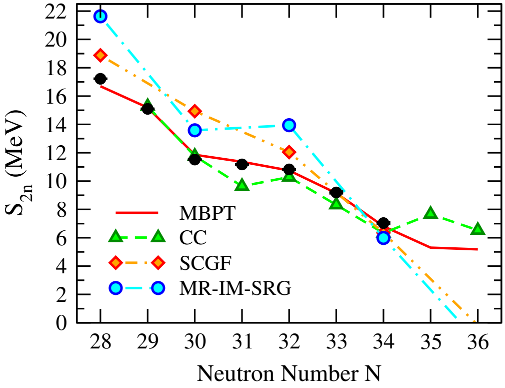
Jones et al.

Nature 465 454 (2010)



Calcium two-neutron separation energies

Measurement of ^{51,52}Ca at TRIUMF and ^{53,54}Ca at ISOLDE



Gallant et al. PRL 109 032506 (2012)
Wienholtz et al. Nature 498 346 (2013)
Hagen et al. PRL 109 032502 (2012)
Somà et al. PRC 89 061301 (2014)
Hergert et al. PRC 90 041302 (2014)

Excellent agreement of MBPT prediction with experiment

S_{2n} evolution:
^{52}Ca–^{54}Ca decrease similar to ^{48}Ca–^{50}Ca unambiguously establishes $N = 32$ shell closure

Phenomenological interactions GXPF1A and KB3G also good description of experiment up to ^{54}Ca

Coupled-cluster, SCGF, IM-SRG reasonable agreement with experiment

Calcium 2_1^+ energies

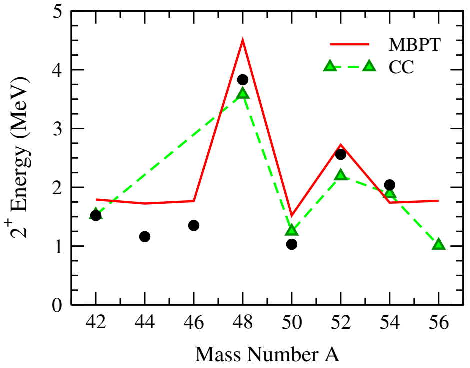
2_1^+ energies characterize shell closures

Correct closure at $N = 28$ when 3N forces are included

Holt et al. JPG39 085111 (2012)

Holt, JM, Schwenk, JPG40 075105 (2013)

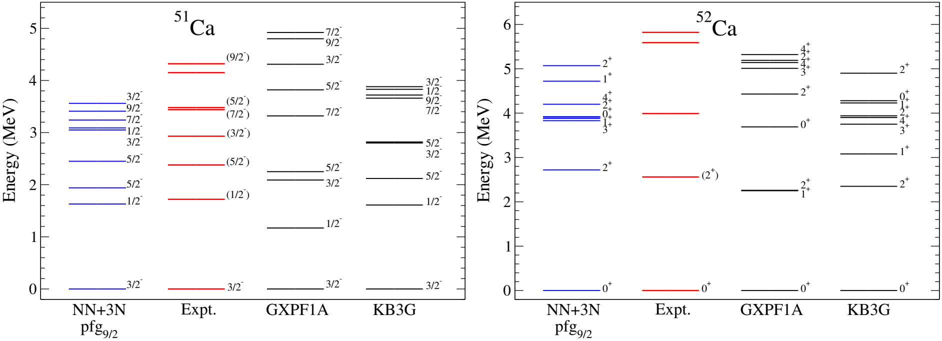
Hagen et al. PRL 109 032502 (2012)



- High 2^+ in ^{32}Ca related to closure at $N = 32$
- Relatively high 2^+ in ^{32}Ca measured at RIBF indicate closure at $N = 34$
  to be confirmed in mass, B(E2) measurements
  Steppenbeck et al. Nature 502 207 (2013)

Excitation spectra

Spectra for neutron-rich calcium isotopes

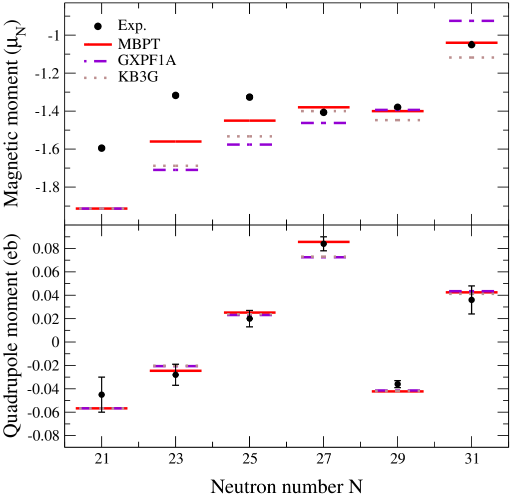


Good agreement with experiment, comparable to phenomenological interactions, and predictions given for heavier systems

Holt, JM, Simonis, Schwenk PRC90 024312 (2014)

Calcium magnetic and quadrupole moments

Electric quadrupole moments and magnetic momentss
in ground states of calcium isotopes measured by COLLAPS at ISOLDE



Consistent description of
ground-state masses
and spectroscopy

Very good agreement to
experiment,
up to neutron-rich systems

Comparable to
phenomenological interactions

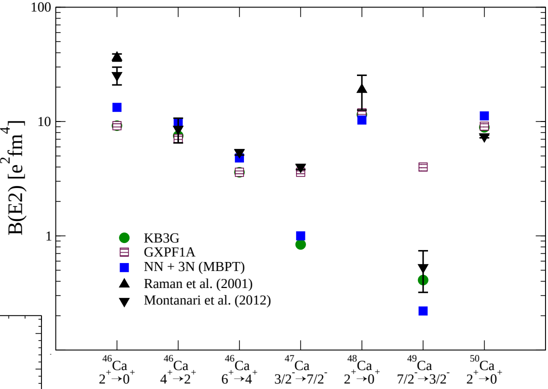
Phenomenological effective
charges $q_n = 0.5e$,
and bare g-factor g_s(bare)

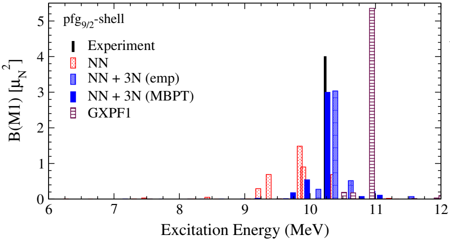
Garcia Ruiz et al.
PRC91 041304 (2015)

Calcium electromagnetic transitions

B(E2)s in reasonable agreement with experiment
span three orders of magnitude

Similar quality as phenomenological interactions





B(M1) strength in ^{48}Ca
NN+3N good agreement
experiment strength and energy
quenched g-factor $g_s = 0.75 g_s$(bare)

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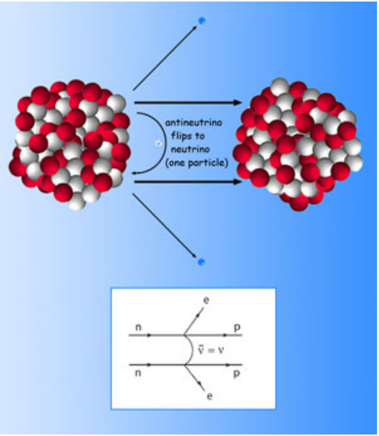
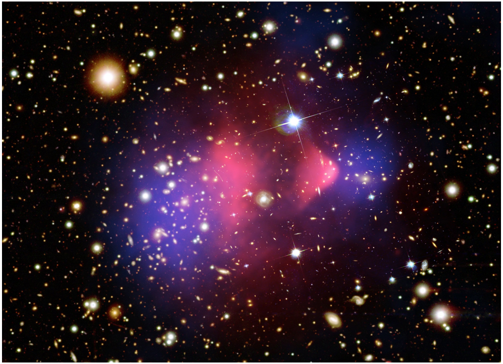
3. Dark Matter scattering off nuclei

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



Neutrinoless double-beta decay

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



Dark matter scattering off nuclei

What is Dark Matter made of?

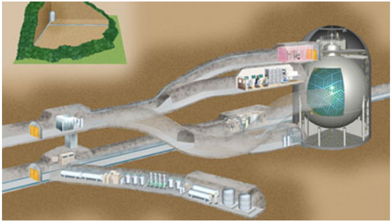
Nuclear physics and fundamental symmetries

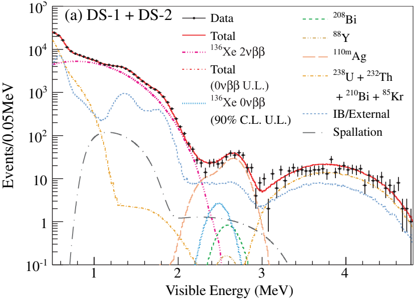
Neutrinos, Dark Matter can be studied with high-energy experiments

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)





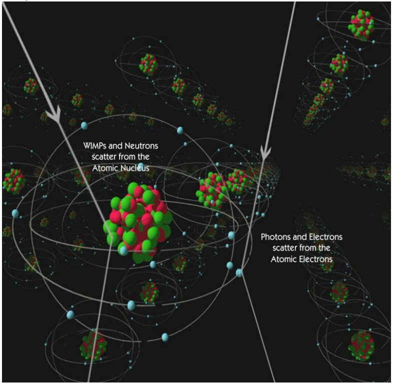
KamLAND-Zen

Nuclear matrix elements

Nuclear matrix elements are needed to study fundamental symmetries

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

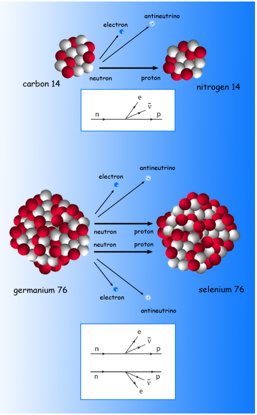
- Nuclear structure calculation of the initial and final states:
  Ab initio, shell model, energy density functional...
- Lepton-nucleus interaction:
  Evaluate (non-perturbative) hadronic currents inside nucleus: phenomenology, effective theory



CDMS Collaboration

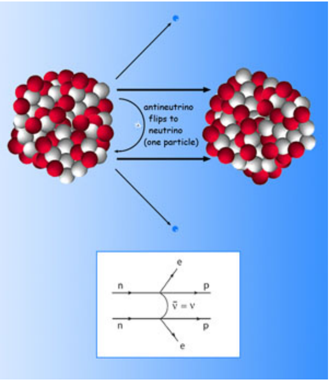
Lepton-number conservation

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

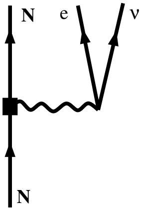


Neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay

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

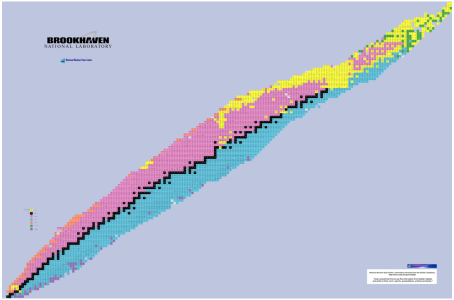
Standard Model: $J_L^{\mu\dagger}$ for quarks, need $J_L^{\mu\dagger}$ for nucleons

In nuclei (non-relativistic), β decay is

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

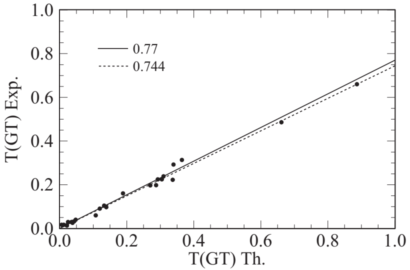
Fermi and Gamow-Teller transitions

corrections (forbidden transitions)
expansion of the lepton current



Gamow-Teller transitions

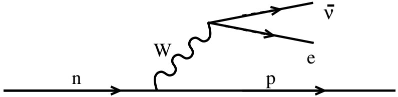
Single-β, $2\nu\beta\beta$ decays well described by nuclear structure: shell model...



Martinez-Pinedo et al. PRC53 2602(1996)

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

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



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

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.

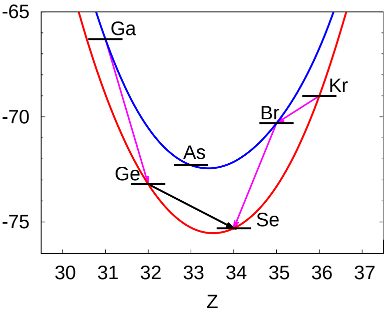
	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
$^{48}Ca \to {}^{48}Ti$	0.047 ± 0.003	0.74	0.047	kb3
$^{48}Ca \to {}^{48}Ti$	0.047 ± 0.003	0.74	0.048	kb3g
$^{48}Ca \to {}^{48}Ti$	0.047 ± 0.003	0.74	0.065	gxpf1
$^{76}Ge \to {}^{76}Se$	0.140 ± 0.005	0.60	0.116	gcn28:50
$^{76}Ge \to {}^{76}Se$	0.140 ± 0.005	0.60	0.120	jun45
$^{82}Se \to {}^{82}Kr$	0.098 ± 0.004	0.60	0.126	gcn28:50
$^{82}Se \to {}^{82}Kr$	0.098 ± 0.004	0.60	0.124	jun45
$^{128}Te \to {}^{128}Xe$	0.049 ± 0.006	0.57	0.059	gcn50:82
$^{130}Te \to {}^{130}Xe$	0.034 ± 0.003	0.57	0.043	gcn50:82
$^{136}Xe \to {}^{136}Ba$	0.019 ± 0.002	0.45	0.025	gcn50:82

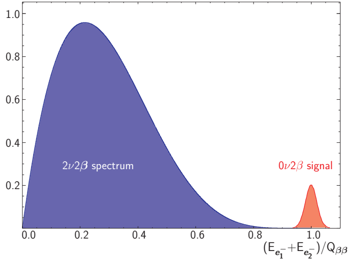
Caurier, Nowacki, Poves PLB711 62(2012)

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





$$2\nu\beta\beta : E_{e_1} + E_{e_2} + E_{\bar{\nu}_1} + E_{\bar{\nu}_2} = Q_{\beta\beta}$$
$$0\nu\beta\beta : E_{e_1} + E_{e_2} = Q_{\beta\beta}$$

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

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

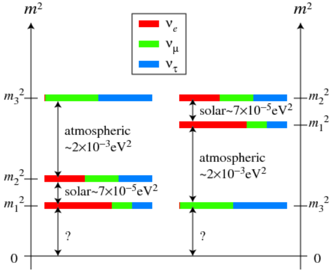
$0\nu\beta\beta$ decay nuclear matrix elements

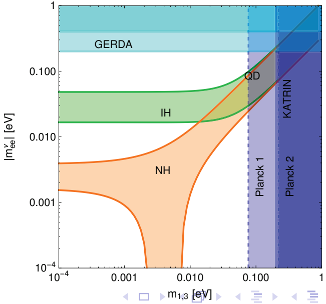
$0\nu\beta\beta$ process needs massive Majorana neutrinos ($\nu = \bar{\nu}$)
$\Rightarrow$ detection would proof Majorana nature of neutrinos

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

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

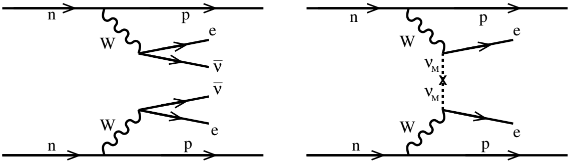
$M^{0\nu\beta\beta}$ is the nuclear matrix element
Identify best experimental isotopes, obtain neutrino mass $m_{\beta\beta} = \left|\sum U_{ek}^2 m_k\right|$





$\beta\beta$ decays and closure approximation

$\beta\beta$ decays are quite different processes



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 trasition operator, via the so-called neutrino potential

Closure approximation, good to 90%, Sen'kov et al. PRC89 054304 (2014)

$$\sum_a \frac{\langle N_f| J_L^{\mu\dagger}(\mathbf{x}) |N_a\rangle \langle N_a| J_L^{\rho\dagger}(\mathbf{y}) |N_i\rangle}{p + E_a - \frac{1}{2}(E_i + E_f)} \simeq \frac{\langle N_f| J_L^{\mu\dagger}(\mathbf{x}) J_L^{\rho\dagger}(\mathbf{y}) |N_i\rangle}{p + \langle E\rangle - \frac{1}{2}(E_i + E_f))}$$

Neutrinoless $\beta\beta$ decay matrix elements

The nuclear matrix element reads

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

- $\tau_n^- \tau_m^-$ transform two neutrons into two protons
- Ω^X is the spin structure:
  Fermi ($\mathbb{1}$), Gamow-Teller ($\sigma_1 \sigma_2$), Tensor $\left(\left[Y^2(\hat{r}) \left[\sigma_1 \sigma_2 \right]^2 \right]^0 \right)$
- $H(r)$ is the neutrino potential

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

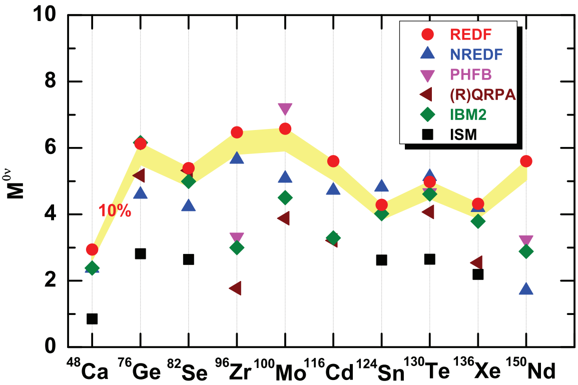
$\Rightarrow$ Virtual neutrinos, $H(r)$, allow all J^P in intermediate states

$\Rightarrow$ Momentum-transfer $p \sim 100$ MeV, closure approximation

$\Rightarrow$ $H(r)$ breaks isospin invariance: three spin structures contribute, but Gamow-Teller part dominant $\sim 85\%$ of total NME

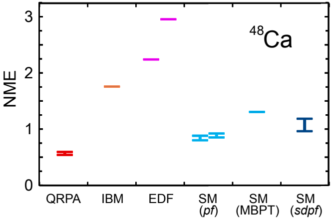
Neutrinoless $\beta\beta$ decay matrix elements

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?

Shell model spectra and occupancies

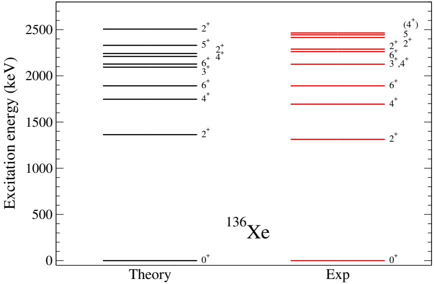
Shell model in one-major-shell spaces with phenomenological interactions

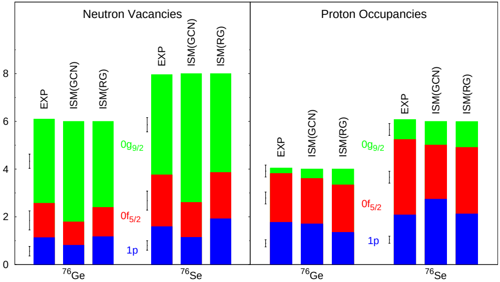
pf-shell, KB3G interaction: ^{48}Ca

$p_{3/2}, p_{1/2}, f_{5/2}, g_{9/2}$ space, GCN2850 interaction: ^{76}Ge, ^{82}Se

$d_{5/2}, s_{1/2}, d_{3/2}, g_{7/2}, h_{11/2}$ space, GCN5082 interaction: ^{124}Sn, ^{130}Te, ^{136}Xe

Experimental excitation spectra and occupancies well reproduced





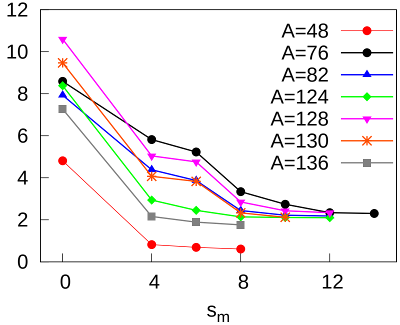
Exp: Schiffer et al. PRL100 112501(2009), Kay et al. PRC79 021301(2009)

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

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

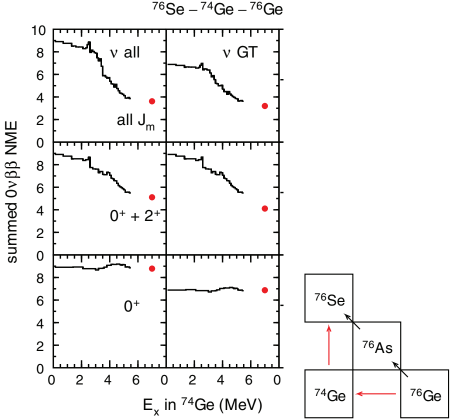
$0\nu\beta\beta$ decay is favoured by pairing correlations

Maximum between superfluid nuclei, reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Related to two-nucleon transfers

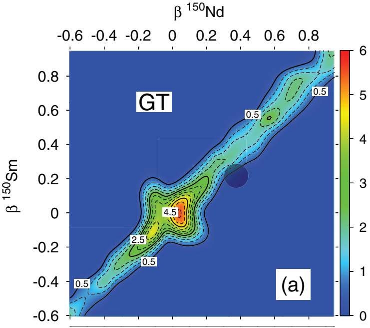


Brown et al. PRL113 262501 (2014)

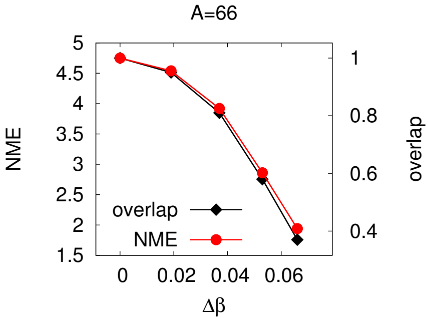
Deformation and $0\nu\beta\beta$ decay

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

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



Rodríguez, Martínez-Pinedo
PRL105 252503 (2010)



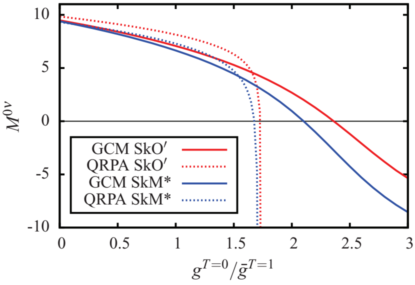
JM, Caurier, Nowacki, Poves
JPCS267 012058 (2011)

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

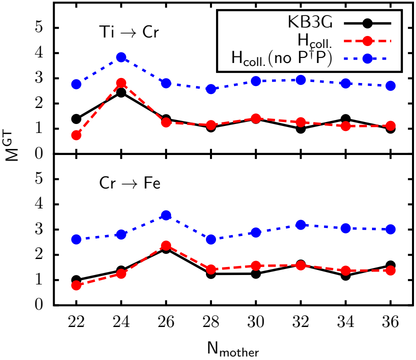
Proton-neutron pairing and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ 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

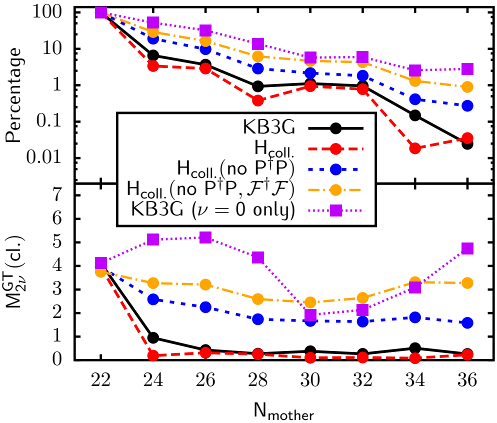
Related to approximate *SU*(4) symmetry of the $0\nu\beta\beta$ decay operator

SU(4) symmetry: small matrix elements

Exact SU(4) symmetry $\Rightarrow M^{0\nu\beta\beta} = 0$
(mother and daughter nuclei in different SU(4) irreps)

SU(4) broken in nuclei
(spin-orbit force...)
but relatively small fraction
of mother and daughter nuclei
in same SU(4) irrep

When neutrino potential is omitted,
$0\nu\beta\beta$ operator exactly
symmetric under SU(4):
Matrix elements almost vanish

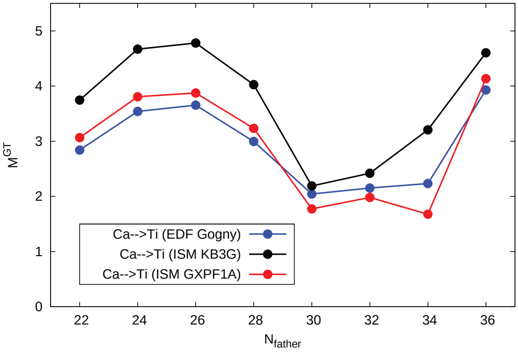


Missing correlations that break SU(4) symmetry, strong impact on $\beta\beta$ decay

$0\nu\beta\beta$ 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

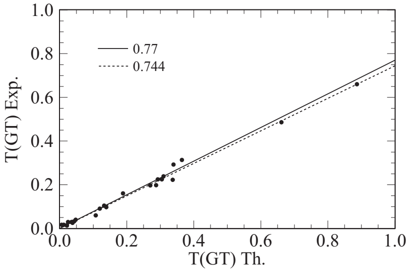
JM, Rodríguez, Martínez-Pinedo, Poves PRC90 024311(2014)

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

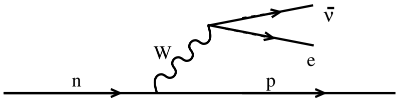
Single-β, $2\nu\beta\beta$ decays well described by nuclear structure: shell model...



Martinez-Pinedo et al. PRC53 2602(1996)

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

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.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
$^{48}Ca \to {}^{48}Ti$	0.047 ± 0.003	0.74	0.047	kb3
$^{48}Ca \to {}^{48}Ti$	0.047 ± 0.003	0.74	0.048	kb3g
$^{48}Ca \to {}^{48}Ti$	0.047 ± 0.003	0.74	0.065	gxpf1
$^{76}Ge \to {}^{76}Se$	0.140 ± 0.005	0.60	0.116	gcn28:50
$^{76}Ge \to {}^{76}Se$	0.140 ± 0.005	0.60	0.120	jun45
$^{82}Se \to {}^{82}Kr$	0.098 ± 0.004	0.60	0.126	gcn28:50
$^{82}Se \to {}^{82}Kr$	0.098 ± 0.004	0.60	0.124	jun45
$^{128}Te \to {}^{128}Xe$	0.049 ± 0.006	0.57	0.059	gcn50:82
$^{130}Te \to {}^{130}Xe$	0.034 ± 0.003	0.57	0.043	gcn50:82
$^{136}Xe \to {}^{136}Ba$	0.019 ± 0.002	0.45	0.025	gcn50:82

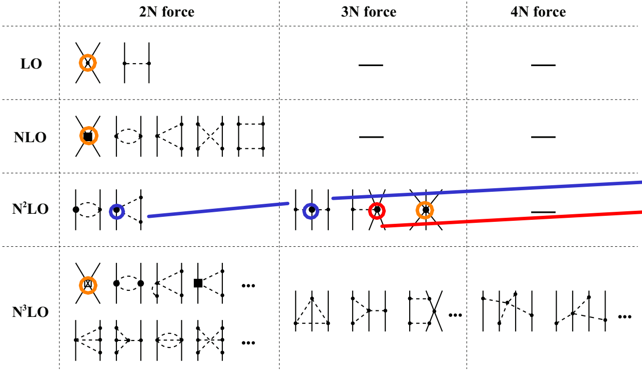
Caurier, Nowacki, Poves PLB711 62(2012)

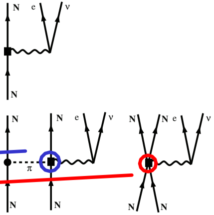
Chiral Effective Field Theory

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...

2b currents in light nuclei

2b currents (meson-exchange currents) tested in light nuclei:

^{3}H β decay

Gazit et al. PRL103 102502(2009)

$A \leq 9$ magnetic moments

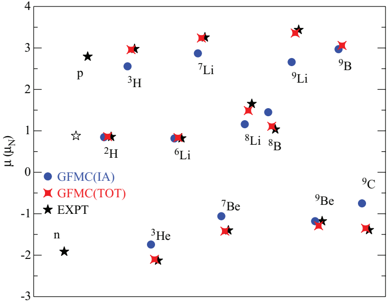
^{8}Be EM transitions

Pastore et al. PRC87 035503(2013)

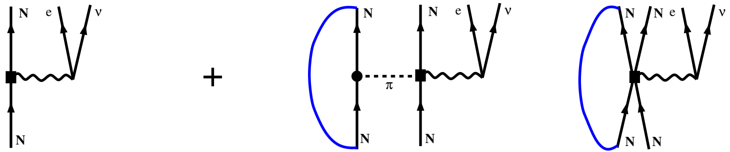
Pastore et al. PRC90 024321(2014)

^{3}H μ capture

Marcucci et al. PRC83 014002(2011)



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

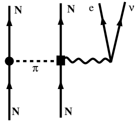


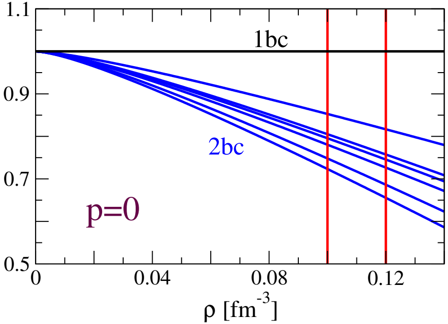
2b currents in medium-mass nuclei

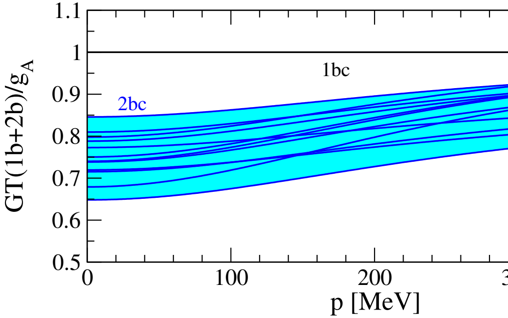
Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

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



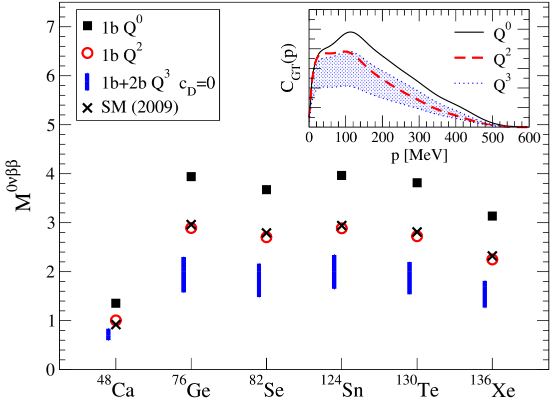




2b currents predict g_A quenching $q = 0.85 \ldots 0.66$

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

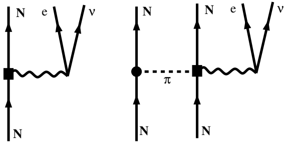
Nuclear matrix elements with 1b+2b currents



JM, Gazit, Schwenk PRL107 062501 (2011)

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

JM, Poves, Caurier, Nowacki NPA818 139 (2009)

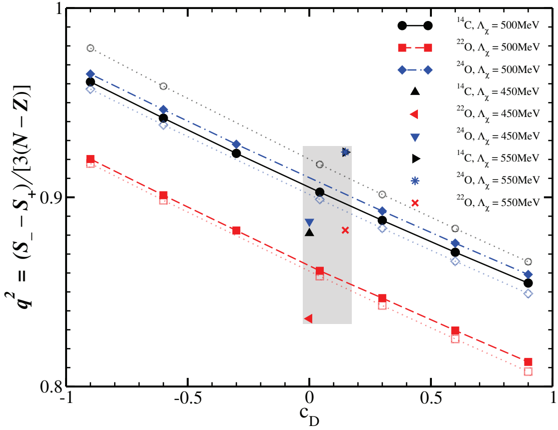


Order Q^3 2b currents reduce NMEs $\sim$ 15% – 40%

Similar quenching obtained in QRPA calculations with same 2b currents

Engel, Šimkovic, Vogel PRC89 064308 (2014)

Very recent Coupled-cluster calculations for single-β decay (GT strengths) including chiral 1b and 2b currents in *p*, low-*sd* nuclei ^{14}C, ^{22}O and ^{24}O



Ekström et al. PRL113 262504 (2014)

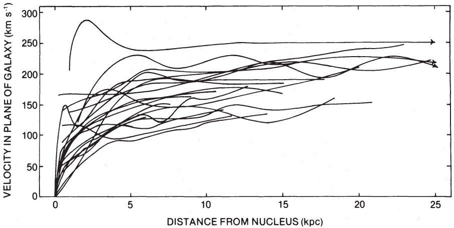
Calculation with chiral NN+3N forces and currents

Dominant effect of 2b currents captured by normal-ordered 1b part with respect to Hartree-Fock state

From 2b currents predict small g_A quenching $q = 0.96...0.92$

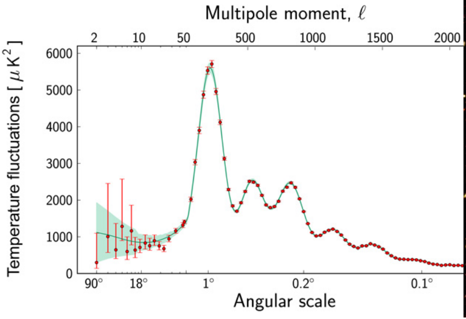
Outline

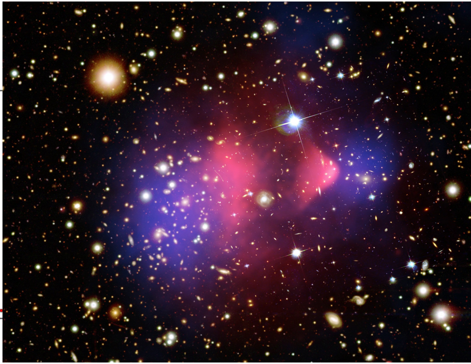
Dark Matter: evidence



Solid evidence of Dark Matter
in very different observations:

Rotation curves, Lensing, CMB...
Zwicky 1930's, Rubin 1970's..., Planck 2010's

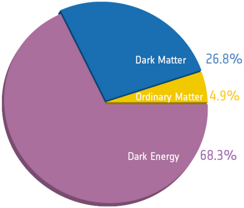




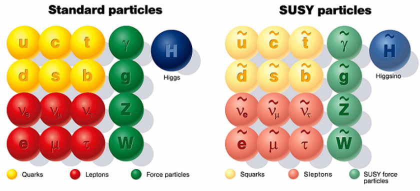
What is Dark Matter made of?

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

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

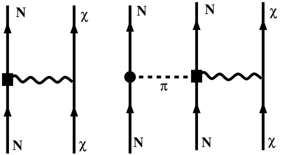


Lightest supersymmetric particles
(usually neutralinos)
predicted in SUSY extensions
of the Standard Model



Expected WIMP-density agrees with observed Dark Matter density

WIMP scattering off nuclei



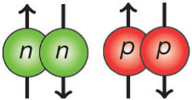
The challenge is direct Dark Matter detection

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

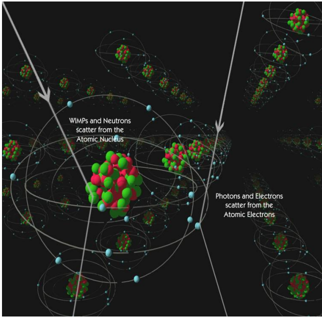
WIMPs couple to the nuclear density

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



CDMS Collaboration

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

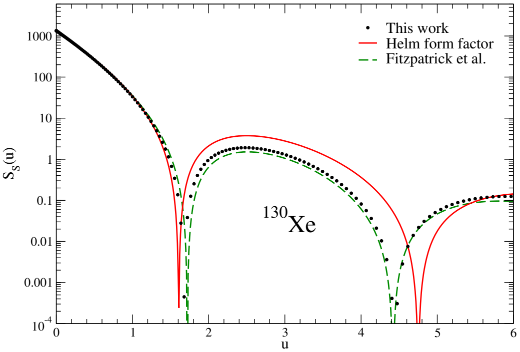
Matrix element of the dark matter scattering: structure factor

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

Spin-independent structure factor for ^{130}Xe

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

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



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

Spin-dependent hadronic currents

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

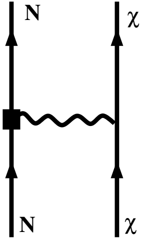
At lowest orders Q^0 and Q^2 in chiral EFT, 1b currents

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

isoscalar isovector

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

axial pseudoscalar



Isoscalar and isovector (distinguish neutrons and protons) components

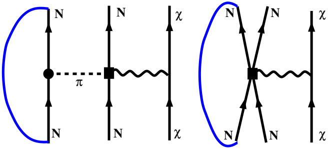
Isovector compoments have axial (dominant) and pseudoscalar term

Spin-dependent 2b currents

Leading Q^3 correction: 2b currents

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

$$\mathbf{J}^3_{12} = -\frac{g_A}{4F_\pi^2}\frac{1}{m_\pi^2+k^2}\left[2\left(c_4+\frac{1}{4m}\right)\mathbf{k}\times(\sigma_\times\times\mathbf{k})\tau^3_\times \right.$$
$$\left. +4c_3\mathbf{k}\cdot\left(\sigma_1\tau^3_1+\sigma_2\tau^3_2\right)\mathbf{k}-\frac{i}{m}\mathbf{k}\cdot(\sigma_1-\sigma_2)\mathbf{q}\tau^3_\times\right]$$



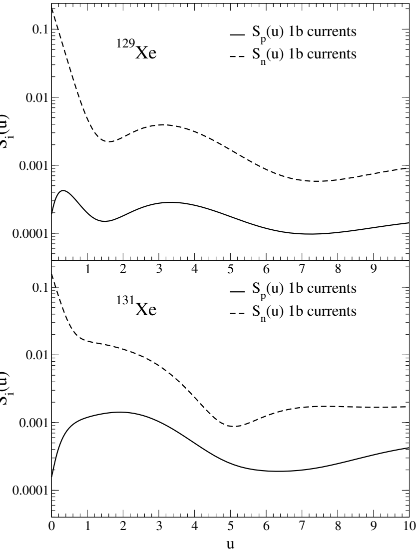
The leading (long-range) normal-ordered two-body currents are

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

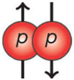
$$\mathbf{J}^{\text{eff}}_{i,\text{2b}} = -g_A\frac{\tau_i^3}{2}\frac{\rho}{F_\pi^2}I(\rho,P=0)\left(\frac{1}{3}(2c_4-c_3)\right)\sigma_i = -g_A\frac{\tau_i^3}{2}\delta a_1\sigma_i$$

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

Renormalize isovector couplings: reduce axial and enhance pseudoscalar



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

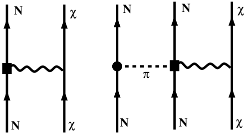


Neutrons carry most nuclear spin

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

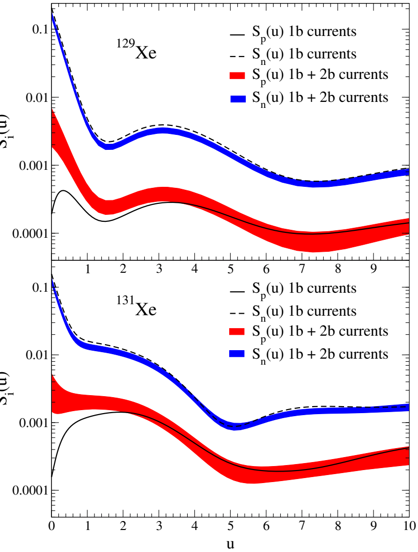
$$S(0) \propto \left| \frac{a_0 + a_1}{2} \langle S_p \rangle + \frac{a_0 - a_1}{2} \langle S_n \rangle \right|^2$$

2b currents involve neutrons + protons:



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

SD Structure Factors with 1b+2b currents



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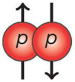

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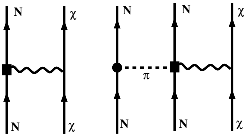
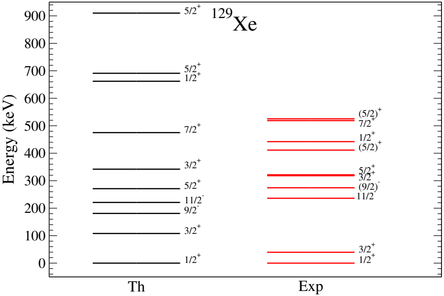
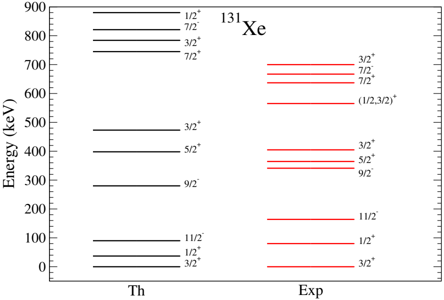


Neutrons always contribute with 2b currents, dramatic increase in $S_p(u)$

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





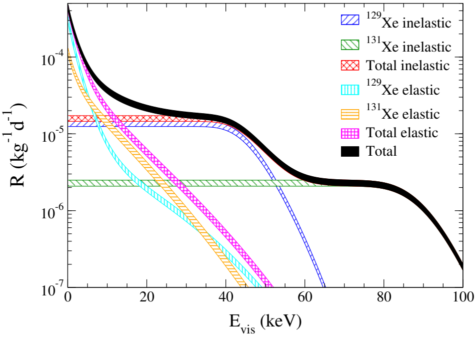
Very low-lying first-excited states $\sim 40, 80$ keV

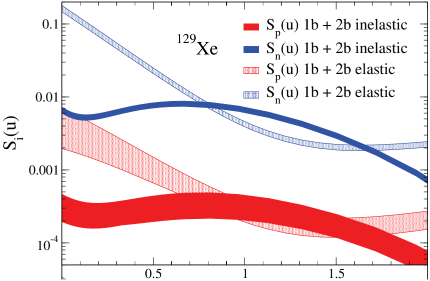
If WIMPs have enough kinetic energy
inelastic scattering possible

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

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

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

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

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

- Shell Model matrix elements smaller than other approaches, but only method to include full correlations in configuration space
- Correlations (deformation, proton-neutron pairing) have strong impact on (reducing) matrix elements
- 2b currents, analogue of 3N forces, modify nuclear matrix elements

WIMP scattering off nuclei for direct Dark Matter detection experiments

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

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