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

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

Institute for Nuclear Theory, 26th June 2018
Nuclear physics, $\beta\beta$ decay, dark matter detection

Nuclear structure crucial for design and interpretation of experiments

Neutrinos, dark matter studied in low-energy experiments using nuclei
Abundant material, long observation time with very low background sensitive to rarest decays and tiny cross-sections!

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

Dark matter: 
\[
\frac{d\sigma_{\chi N}}{dq^2} \propto \left| \sum_i c_i \zeta_i F_i \right|^2
\]

$M^{0\nu\beta\beta}$: Nuclear matrix element
$F_i$: Nuclear structure factor
Nuclear matrix elements and structure factors

Nuclear matrix elements needed to study fundamental symmetries

\[
\langle \text{Final} | L_{\text{leptons-nucleons}} | \text{Initial} \rangle = \langle \text{Final} | \int dx j^\mu(x) J_\mu(x) | \text{Initial} \rangle
\]

- **Nuclear structure calculation** of the initial and final states:
  Quantum Monte Carlo, no-core shell model, coupled cluster shell model, energy density functional

- **Lepton-nucleus interaction:**
  Evaluate (non-perturbative) hadronic currents inside nucleus:
  phenomenology, effective theory
1. Lepton number violation, neutrino nature: neutrinoless $\beta\beta$ decay

2. Direct detection of dark matter: dark matter scattering off nuclei

3. Summary
Outline

1. Lepton number violation, neutrino nature: neutrinoless $\beta\beta$ decay

2. Direct detection of dark matter: dark matter scattering off nuclei

3. Summary
Neutrinoless $\beta\beta$ decay

Lepton-number violation, Majorana nature of neutrinos

Second order process only observable in rare cases with $\beta$-decay energetically forbidden or hindered by $\Delta J$

![Graph showing binding energies and atomic numbers for various isotopes]

Best limits: $^{76}$Ge (GERDA), $^{130}$Te (CUORE), $^{136}$Xe (EXO, KamLAND-Zen)
Next generation experiments: inverted hierarchy

The decay lifetime is

\[ T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)^{-1} = G_{01} |M_{0\nu\beta\beta}|^2 m_{\beta\beta}^2 \]

sensitive to absolute neutrino masses, \( m_{\beta\beta} = |\sum U_{e k}^2 m_k| \), and hierarchy

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

KamLAND-Zen, PRL117 082503(2016)
Large difference in nuclear matrix element calculations: factor $\sim 2 - 3$

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

$\Omega^X = \text{Fermi} (\mathbb{1}), \text{GT} (\sigma_n \sigma_m), \text{Tensor}$

$H(r) = \text{neutrino potential}$

**Ab initio quantum Monte Carlo $0\nu\beta\beta$:** Pastore et al. PRC97 014606(2018)

**Phenomenological many-body:** shell model, energy-density functional theory, QRPA...
Shell model

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

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

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

$$H |\psi\rangle = E |\psi\rangle \rightarrow H_{\text{eff}} |\psi\rangle_{\text{eff}} = E |\psi\rangle_{\text{eff}}$$

$$|\psi\rangle_{\text{eff}} = \sum_{\alpha} c_\alpha |\phi_\alpha\rangle, \quad |\phi_\alpha\rangle = a_{i_1}^+ a_{i_2}^+ ... a_{i_A}^+ |0\rangle$$

Exact diagonalization: $10^{11}$ dimension Caurier et al. RMP 77 427 (2005)
Monte Carlo shell model: $10^{23}$ dimension Togashi et al. PRL 117 172502 (2016)
For $^{48}\text{Ca}$ enlarge shell model configuration space from $pf$ to $sdpf$ (4 to 7 orbitals) restricted to $2\hbar\omega$ excitations. Dimension of $^{48}\text{Ti}$ calculation increases from less than $10^6$ to over $10^9$.

The $0^+_{2}$ state in $^{48}\text{Ca}$ is brought down by 1.3 MeV in the $sdpf$ calculation. Good agreement to experiment and with the associated two-proton transfer cross section ($2\hbar\omega$ states dominant in $^{48}\text{Ca}$ $0^+_{2}$).

The difference in the $^{48}\text{Ca}$ two-neutrino $\beta\beta$ decay matrix element is about 5% between $pf$ and $sdpf$ calculations.
Shell model matrix elements in two shells

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

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

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

Nuclear matrix element increases moderately 30%
Iwata et al. PRL116 112502 (2016)

Likewise, very mild effect found in GCM calculations of $^{76}\text{Ge}$
Jiao et al. PRC96 054310 (2017)
Pairing correlations and $0^{\nu}\beta\beta$ decay

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

Ideal case: superfluid nuclei reduced with high-seniorities

Addition of isoscalar pairing reduces matrix element value

Related to approximate $SU(4)$ symmetry of the $\sum H(r)\sigma_i\sigma_j\tau_i\tau_j$ operator
Gamow-Teller $\beta$ decay: “quenching”

Gamow-Teller $\beta$ decays described well by nuclear structure (shell model) but...

\[
\langle F | \sum_i g_{A_i}^{\text{eff}} \sigma_i \tau_i^- | I \rangle
\]

\[g_{A_i}^{\text{eff}} = q g_A, \quad q \sim 0.7 - 0.8.\]

Theory needs to “quench” $\sigma \tau$ operator to reproduce experimental lifetimes: problem in nuclear many-body wf or operator?

This puzzle has been the target of many theoretical efforts:

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

Martínez-Pinedo et al. PRC53 2602 (1996)
Oxygen dripline using chiral NN+3N forces correctly reproduced ab-initio calculations treating explicitly all nucleons. Excellent agreement between different approaches.

No-core shell model (Importance-truncated)

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

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

Coupled-clusters
Jansen et al. PRL113 142502(2014)
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies
Approximate chiral symmetry: pion exchanges, contact interactions
Systematic expansion: nuclear forces and electroweak currents

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

Park, Baroni, Krebs...

2b currents applied to $\nu d$ scattering (SNO), $^3H$ $\beta$-decay, $\mu$ moment...

Javier Menéndez (CNS, U. Tokyo)

$0\nu\beta\beta$ decay and dark matter detection
2b currents in medium-mass nuclei

Normal-ordered 2b currents modify GT operator
JM, Gazit, Schwenk PRL107 062501 (2011)

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

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 \( p \sim m_\pi \)
Quantum Monte Carlo, No Core Shell Model $\beta$ decays in $A \leq 10$

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

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

Impact of 2b currents small (few %), disagreement on sign
β decay in medium-mass nuclei: IMSRG

“Quenching” of $g_A$ in Gamow-Teller Decays

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

Minor effect from consistent effective operator

Significant effect from neglected 2-body currents

Ab initio calculations explain data with unquenched $g_A$

From J. Holt, INT-18-1a program
Short-range correlations

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

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

Correlation function defined by

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

Impact on $0\nu\beta\beta$ decay
nuclear matrix elements small $\sim 10\%$
Open questions: transition operator

Contact light-neutrino operator

Cirigliano et al. PRL120 202001(2018)

Unknown coupling value
E. Mereghetti’s talk

Short-range character

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

Estimated effect $\sim 10\%$


compared to $\sim 20\%$
in GT $\beta$ decay ("quenching")

JM et al. PRL107 062501(2011)
Tests of nuclear structure

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

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

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

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

$\mu$-capture, $\nu$-nucleus scattering many multipoles ($J$ values), like $0\nu\beta\beta$ decay
Gamow-Teller (GT) strength distributions well described by theory (quenched)

\[ d\sigma/d\Omega (\theta = 0) \propto \sum_i \sigma_i \tau^\pm \]

\[ \langle 1^+_f \mid \sum_i g_{\text{eff}} \sigma_{i,\tau^\pm} \mid 0^+_\text{gs} \rangle, \quad g_{\text{eff}} \approx 0.7 g_A \]

GT strengths combined related to $2\nu\beta\beta$ decay, but relative phase unknown
Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance in double charge-exchange reactions $^{48}\text{Ca}(pp,nn)^{48}\text{Ti}$ proposed in 80’s
Auerbach, Muto, Vogel... 1980’s, 90’s

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

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

Shell model calculation
Shimizu, JM, Yako, PRL120 142502 (2018)

$$B(DGT^{-}; \lambda; i \rightarrow f) = \frac{1}{2J_i + 1} \left| \langle ^{48}\text{Ti} | \sum_i \sigma_i \tau_i^\lambda \times \sum_j \sigma_j \tau_j^\lambda | ^{48}\text{Ca}_{gs} \rangle \right|^2$$
DGT transition to ground state

\[ M_{DGT} = \sqrt{B(DGT; 0^+_gs \rightarrow 0^+_gs)} \]

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

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

Common to shell model and energy-density functional theory

\[ 0 \lesssim M^{0\nu\beta\beta} \lesssim 5 \]

disagreement to QRPA

Shimizu, JM, Yako,
PRL120 142502 (2018)
Short-range character of DGT, $0\nu\beta\beta$ decay

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

Bogner et al. PRC86 064304 (2012)

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

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

Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako, PRL120 142502 (2018)
1. Lepton number violation, neutrino nature: neutrinoless $\beta\beta$ decay

2. Direct detection of dark matter: dark matter scattering off nuclei

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

Rotation curves, Lensing, CMB...
Zwicky 1930’s, Rubin 1970’s..., Planck 2010’s
Direct detection of dark matter

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

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

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

Theory: most efficient analysis of experiments covering widest range of WIMP-nucleus interactions
Present experiments show no evidence for dark matter, in spite of some unconfirmed claims.

Exclusion plots restrict dark matter coupling to Standard Model fields.

Standard analyses consider simplest “spin-independent” (scalar-scalar) and sometimes “spin-dependent” (axial-axial) isovector couplings.
WIMP scattering off nuclei
interplay of particle, hadronic and nuclear physics:
WIMPs: interaction with quarks and gluons
Quarks and gluons: embedded in the nucleon
Nucleons: form complex, many-nucleon nuclei

General WIMP-nucleus scattering cross-section:

$$\frac{d\sigma_{\chi N}}{dq^2} \propto \left| \sum_i c_i \zeta_i F_i \right|^2$$

$\zeta$: kinematics ($q^2$, $\cdots$)

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

$F$ functions: $F^2 \sim$ structure factor, nuclear structure physics
Nuclear structure for xenon

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

Agreement to experimental excitation spectra very good

Calculations with 5 orbitals for protons, neutrons: max dimension $4 \times 10^8$
Nuclear structure for xenon

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

Agreement to experimental excitation spectra very good

Calculations with 5 orbitals for protons, neutrons: max dimension $4 \times 10^8$

arXiv:1804.08995
Nuclear structure for dark matter scattering targets

Similar level of agreement in other light / medium-mass nuclei studied
WIMP scattering off nuclei: standard analysis

Standard direct detection analyses consider two very different cases

**Spin-Independent (SI) interaction:**
WIMPs couple to the nuclear density \( (\chi_1 N) \)

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

Cross section enhancement by factor
\[
| \sum_A \langle N | 1_N | N \rangle |^2 = A^2
\]

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

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

Cross section scale set by single-proton/neutron spin expectation value
\[
| \sum_A \langle N | \mathbf{S}_N | N \rangle |^2 = \langle \mathbf{S}_n \rangle^2, \langle \mathbf{S}_p \rangle^2 \sim 0.1
\]
Non-relativistic effective field theory

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

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

Fitzpatrick et al. JCAP02 004(2013), Anand et al. PRC90 065501 (2014)

Interferences occur between some of the terms, which map into 6 different nuclear responses \( M \) (SI scattering), \( \Sigma, \Sigma' \) (SD scattering), \( \Delta, \Phi'', \Phi' \) (new responses)

\( \Rightarrow \) nuclear structure calculations to interpret dark matter detection data
Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and currents

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Park et al.

Short-range couplings fitted to experiment once

Weinberg, van Kolck, Kaplan, Savage, Meißner, Epelbaum, Weise...
### Chiral EFT WIMP-nucleus interactions

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

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\[
\mathcal{M}^{SS}_{1, NR} = \mathcal{O}_1 f_N(t) \\
\mathcal{M}^{SP}_{1, NR} = \mathcal{O}_{10} g_5^N(t) \\
\mathcal{M}^{PP}_{1, NR} = \frac{1}{m_\chi} \mathcal{O}_6 h_5^N(t) \\
\mathcal{M}^{VV}_{1, NR} = \mathcal{O}_1 \left( f_{1, V}^N(t) + \frac{t}{4 m_N^2} f_{2, V}^N(t) \right) + \frac{1}{m_N} \mathcal{O}_3 f_{2, V}^N(t) + \frac{1}{m_N m_\chi} \left( t \mathcal{O}_4 + \mathcal{O}_6 \right) f_{2, V}^N(t) \\
\mathcal{M}^{AV}_{1, NR} = 2 \mathcal{O}_8 f_{1, V}^N(t) + \frac{2}{m_N} \mathcal{O}_9 \left( f_{1, V}^N(t) + f_{2, V}^N(t) \right) \\
\mathcal{M}^{AA}_{1, NR} = -4 \mathcal{O}_4 g_A^N(t) + \frac{1}{m_N^2} \mathcal{O}_6 g_P^N(t) \\
\mathcal{M}^{VA}_{1, NR} = \left\{ -2 \mathcal{O}_7 + \frac{2}{m_\chi} \mathcal{O}_9 \right\} h_A^N(t)
\]

Hoferichter, Klos, Schwenk PLB 746 410 (2015)

**Chiral EFT hierarchy to be complemented with nuclear effects (coherence)**
Coherent contributions from 2b currents:
\( \pi \) coupling, via scalar current and energy-momentum tensor \( \theta^\mu_\mu \)

2b scalar currents also explored by Cirigliano et al.
JHEP10 25(2012)
PLB739 293(2014)

Hoferichter et al. PRD94 063505 (2016)
Generalized coherent scattering

Generalized spin-independent scattering cross section:

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

Fieguth et al. PRD97 103532 (2018)

In addition, interference terms between different contributions
Generalized coherent scattering with interferences

Many different coherent contributions when including interferences

![Graph showing structure factors for 40Ar](image)

Hoferichter, Klos, JM, Schwenk, in preparation
Once dark matter scattering off nuclei is observed, key to unveil nature of dark matter-nucleus interaction.

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

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

Fieguth et al. PRD97 103532 (2018)
Spin-dependent scattering: coupling to one nucleon

\[ \langle S_n \rangle \gg \langle S_p \rangle, \]

Neutrons carry most nuclear spin

\[ S_n = \sum_{i=1}^{N} \sigma_i / 2, \quad S_p = \sum_{i=1}^{Z} \sigma_i / 2 \]

\[ \frac{\mathcal{F}_A(0)^2}{2J+1} = \frac{(J+1)}{\pi J} |a_p \langle S_p \rangle + a_n \langle S_n \rangle|^2 \]

\[ a_n/p = (a_0 \mp a_1)/2, \]

\[ \mathcal{F}_n(0)^2 \propto |\langle S_n \rangle|^2, \quad \mathcal{F}_p(0)^2 \propto |\langle S_p \rangle|^2 \]

Couplings more sensitive to protons \((a_0 = a_1)\)
neutrons \((a_0 = -a_1)\)
Spin-dependent scattering: coupling to two nucleons

\[ \langle S_n \rangle \gg \langle S_p \rangle, \]

Neutrons carry most nuclear spin

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

2b currents naturally involve both neutrons and protons:

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

Impact on dominant species \(\sim 20\%\)
2b contributions make xenon SD results (more sensitive to neutrons) competitive for WIMP-proton cross-section LUX Coll. PRL118 251302 (2017)
Inelastic WIMP scattering off a nucleus?

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

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

\[ p_\pm = \mu v_i \left( 1 \pm \sqrt{1 - \frac{2E^*_i}{\mu v_i^2}} \right) \]
Inelastic WIMP scattering off xenon

Inelastic structure factors compete with elastic ones around \( q \sim 100 \text{ MeV} \) in the kinematically allowed region.

Integrated spectrum for xenon: inelastic scattering signal including \( \gamma \)-ray from decay of excited state

One “plateau” to be detected for each nuclear excitation

Signal of spin-dependent scattering

Baudis et al. PRD88 115014 (2013)
1. Lepton number violation, neutrino nature: neutrinoless $\beta\beta$ decay

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Summary

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

Neutrinoless $\beta\beta$ decay:

- Improve matrix elements in larger configuration spaces with all relevant correlations
- Ab initio with 2b currents free from $\beta$ decay “quenching”
- Double Gamow-Teller transitions correlated to $0\nu\beta\beta$ decay

Direct dark matter detection:

- Need to consider generalized WIMP-nucleon couplings discriminated by $q$-dependence
- 2b currents WIMP coupling to pion (scalar, $\theta$ coupling)
- 2b currents key in SD scattering

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