Nuclear Matrix Elements for Fundamental Symmetries

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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 $N_A = 6.02 \times 10^{23}$ 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)
Nuclear matrix elements are needed to study fundamental symmetries

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

- **Nuclear structure calculation** of the initial and final states:  
  Ab initio, shell model, energy density functional...

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

Lepton number conserved in all processes observed to date

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

$\beta$ decay, $2\nu\beta\beta$ decay...

Neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay
Weak transitions in nuclei

$\beta$ 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), $\beta$ decay is

$$\langle F | \sum_i g_V \tau_i^- + g_A \sigma_i \tau_i^- | I \rangle$$

Fermi and Gamow-Teller transitions

corrections (forbidden transitions)

expansion of the lepton current
Gamow-Teller transitions

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

Martinez-Pinedo et al. PRC53 2602(1996)

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

\[ \langle F | \sum_i g_A^{\text{eff}} \sigma_i \tau_j^- | l \rangle, \quad g_A^{\text{eff}} \approx 0.7 g_A \]

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-$\beta$-decay is energetically forbidden or hindered by large $\Delta J$


\( \beta \beta \) decays

\( \beta \beta \) decays are quite different processes

\[
\frac{E_{e_1} + E_{e_2}}{Q_{\beta \beta}}
\]

\(2\nu\beta\beta\):

\[
E_{e_1} + E_{e_2} + E_{\bar{\nu}_1} + E_{\bar{\nu}_2} = Q_{\beta \beta}
\]

\(0\nu\beta\beta\):

\[
E_{e_1} + E_{e_2} = Q_{\beta \beta}
\]

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: \(^{76}\text{Ge}\) (GERDA), \(^{136}\text{Xe}\) (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 ($\nu = \bar{\nu}$) ⇒ detection would proof Majorana nature of neutrinos

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

$M^{0\nu\beta\beta}$ 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-$\beta$ 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

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

EDF, IBM, QRPA
large matrix elements:
How well they include nuclear structure correlations?
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

Related to two-nucleon transfers

Caurier et al. PRL100 052503 (2008)

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

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)

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, 2νββ decays well described by nuclear structure: shell model...

\[
\left\langle F \right\rvert \sum_i g_i^{\text{eff}} \sigma_i \tau_i^- \left\lvert I \right\rangle, \quad g_A^{\text{eff}} \approx 0.7 g_A
\]

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

Martinez-Pinedo et al. PRC53 2602(1996)

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

Table 2

<table>
<thead>
<tr>
<th>Decay</th>
<th>M^{2\nu}(\text{exp})</th>
<th>q</th>
<th>M^{2\nu}(\text{th})</th>
<th>INT</th>
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<tr>
<td>48Ca → 48Ti</td>
<td>0.047 ± 0.003</td>
<td>0.74</td>
<td>0.047</td>
<td>kb3</td>
</tr>
<tr>
<td>48Ca → 48Ti</td>
<td>0.047 ± 0.003</td>
<td>0.74</td>
<td>0.048</td>
<td>kb3g</td>
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<td>48Ca → 48Ti</td>
<td>0.047 ± 0.003</td>
<td>0.74</td>
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<td>76Ge → 76Se</td>
<td>0.140 ± 0.005</td>
<td>0.60</td>
<td>0.116</td>
<td>gcn28:50</td>
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<tr>
<td>76Ge → 76Se</td>
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<tr>
<td>82Se → 82Kr</td>
<td>0.098 ± 0.004</td>
<td>0.60</td>
<td>0.126</td>
<td>gcn28:50</td>
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<tr>
<td>82Se → 82Kr</td>
<td>0.098 ± 0.004</td>
<td>0.60</td>
<td>0.124</td>
<td>jun45</td>
</tr>
<tr>
<td>128Te → 128Xe</td>
<td>0.049 ± 0.006</td>
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<td>0.059</td>
<td>gcn50:82</td>
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<tr>
<td>130Te → 130Xe</td>
<td>0.034 ± 0.003</td>
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<td>0.043</td>
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<tr>
<td>136Xe → 136Ba</td>
<td>0.019 ± 0.002</td>
<td>0.45</td>
<td>0.025</td>
<td>gcn50:82</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>2N force</th>
<th>3N force</th>
<th>4N force</th>
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<td>N^3LO</td>
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<td><img src="image6.png" alt="Diagram" /></td>
<td><img src="image7.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

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 \(\beta\) 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 \(\mu\) 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)

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

2b currents predict \( g_A \) quenching \( q = 0.85...0.66 \)
Quenching reduced at \( p > 0 \), relevant for 0\( \nu \beta\beta \) decay where \( p \sim m_\pi \)
Nuclear matrix elements with $1b+2b$ currents

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 $\beta$ 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

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

\[ j(r) = \bar{\chi} \chi = \delta_{s_f s_i} e^{-iqr} \] is the leptonic (WIMP) scalar current

\[ S(r) = c_0 \sum_{i=1}^A \delta^3(r-r_i) \] is the hadronic scalar current

\[ j^\mu(r) = \bar{\chi} \gamma^\mu \gamma^5 \chi e^{-iqr} \] is the leptonic (WIMP) axial current

\[ J^{\text{A}}_\mu(r) = \sum_{i=1}^A J^{\text{A}}_{\mu,i}(r) \delta^3(r-r_i) \] is the hadronic axial current

Matrix element of the dark matter scattering: structure factor

\[
S_S(q) + S_A(q) = \frac{1}{4\pi G_F^2} \sum_{s_f,s_i} \sum_{M_f,M_i} \left| \langle J_f M_f | \mathcal{L}_\chi^{\text{SI}} + \mathcal{L}_\chi^{\text{SD}} | J_i M_i \rangle \right|^2
\]
Spin-independent structure factor for $^{130}\text{Xe}$

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

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

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
In $^{129,131}\text{Xe} \langle S_n \rangle \gg \langle S_p \rangle$, 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 $S_p(u)$
In $^{129,131}$Xe $\langle S_n \rangle \gg \langle S_p \rangle$, Neutrons carry most nuclear spin.

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2b currents involve neutrons + protons:

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 $\Rightarrow$ 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
Collaborators

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G. Kessler

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