Status and future of neutrinoless $\beta\beta$ decay nuclear matrix elements

Javier Menéndez

JSPS Fellow, The University of Tokyo

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Lepton number is conserved in all physical processes observed to date.

Uncharged massive particles like Majorana neutrinos ($\nu$) theoretically allow lepton number violation.

\[ \beta \text{ decay, } \beta\beta \text{ decay...} \]

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

Double-beta decay is a second-order process, only to be observed when single-$\beta$ decay is energetically forbidden or hindered by large spin difference between initial and final states.

![Graph showing binding energy vs. atomic number with isotopes and transitions marked.]

Present lifetime limits in $^{76}$Ge, $^{136}$Xe set to $T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y, $10^{26}$ y!
$0\nu\beta\beta$ decay mechanisms

$0\nu\beta\beta$ process needs massive Majorana neutrinos ($\nu = \bar{\nu}$), but several mechanisms mediating the decay are possible

\[
\left(T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right)^{-1} = \sum_i G_i \left|M_{i}^{0\nu\beta\beta}\right|^2 (\eta_i)^2
\]

$G_i$ is the phase space factor: $Q_{\beta\beta}$, leptons...

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

$\eta_i$ describes new physics

Exchange of
Standard Model neutrinos ($\eta = m_{\beta\beta}$),
sterile neutrinos ($\eta \sim m_{\nu}$),
left-right symmetric models ($\eta \sim W_R$ mass, $W_R - W_L$ mixing),
exchange of supersymmetric particles ($\eta \sim$ LNV couplings)

Possible to constrain new physics beyond neutrino masses
Standard Model and new physics

Exchange of Standard Model neutrinos: standard scenario
Exchange of heavy particles test new physics

For the exchange of heavy particles pion physics plays key role, long-range terms dominant in EFT expansion Prezeau et al. PRD68 034016(2003) short-range diagrams additionally suppressed: nucleons $\sim 1$ fm away

Input from Lattice QCD A. Walker-Loud plenary talk
Neutrino mass hierarchy

The decay lifetime is

\[
\left( T^{0\nu\beta\beta}_{1/2} (0^+ \rightarrow 0^+) \right)^{-1} = G_{01} | M^{0\nu\beta\beta} |^2 \left( \frac{m_{\beta\beta}}{m_e} \right)^2 ,
\]

sensitive to absolute neutrino masses, \( m_{\beta\beta} = | \sum U^2_{e_k} m_k | \), and hierarchy

Matrix elements needed to make sure KamLAND-Zen collaboration next generation one-tonne experiments fully cover inverted hierarchy region

KamLAND-Zen collaboration
The Nuclear Matrix Element of the process has to be evaluated

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

Nuclear structure calculation of the initial and final states:
Ab initio, phenomenological...

Description of the lepton-nucleus interaction:
Evaluation (non-perturbative) of the hadronic currents inside nucleus:
phenomenological, effective theory
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...
Nuclear structure with chiral EFT forces

Great success prediction of oxygen dripline and calcium separation energies

Hergert et al. PRL110 242501 (2013)
Cipollone et al. PRL111 062501 (2013)
Jansen et al. PRL113 142502 (2014)

Gallant et al. PRL 109 032506 (2012)
Hagen et al. PRL 109 032502 (2012)
Somà et al. PRC 89 061301 (2014)
Hergert et al. PRC 90 041302 (2014)
Nuclear shell model (Configuration Interaction)

Nuclear shell model configuration space only keep essential degrees of freedom

- Outer orbits: always empty
- Valence space: where many-body problem is solved
- Inner core: always filled

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

$$|\psi\rangle_{\text{eff}} = \sum_\alpha c_\alpha |\phi_\alpha\rangle, \quad |\phi_\alpha\rangle = a_{i1}^+ a_{i2}^+ ... a_{iA}^+ |0\rangle$$

Many-body perturbation theory to generate $H_{\text{eff}}$
very recently non-perturbative methods:
VS-IMSRG, CCEI also available

Shell model codes diagonalize up to
Exact: $\sim 10^{10}$ Slater det. Caurier et al. RMP 77 (2005)
Approximate: $\sim 10^{20}$ Slater det. Togashi et al. PRL 117 (2016)
Excitation spectra

For $0\nu\beta\beta$ decay candidates very good agreement with experiment


Other quantities such as electromagnetic transitions, occupation numbers... also in good agreement to experiment

Phenomenological calculations, systematic uncertainties difficult to quantify
The matrix element is

\[ M^{0\nu\beta\beta} = \langle 0^+_f | \sum_{n,m} \tau^-_n \tau^-_m \sum_X H^X(r) \Omega^X | 0^+_i \rangle \]

- \( \tau^-_n \tau^-_m \) transform two neutrons into two protons
- \( \Omega^X \) is the spin structure:
  - Fermi (1), Gamow-Teller (\( \sigma_n \sigma_m \)), Tensor \( [Y^2(\hat{r}) [\sigma_n \sigma_m]^2]^0 \)
- \( H(r) \) is the neutrino potential, depends on \( m_\nu \)

\[
H^X(r) = \frac{2}{\pi} \frac{R}{g_A^2(0)} \int_0^\infty f^X(pr) \frac{h^X(p^2)}{(\sqrt{p^2 + m_\nu^2})(\sqrt{p^2 + m_\nu^2 + \langle E^m \rangle - \frac{1}{2} (E_i - E_f)})} p^2 dp \sim \frac{R}{r}
\]

\( 2\nu\beta\beta \) decay: momentum transfer limited by \( Q_{\beta\beta} \)

\( 0\nu\beta\beta \) decay: larger momentum transfers, \( p \sim 100 - 200 \text{ MeV} \), set by typical distance between the two decaying nucleons
Neutrinoless $\beta\beta$ decay matrix elements

Large difference in nuclear matrix element calculations: factor $\sim 2 - 3$

EDF, IBM, QRPA large matrix elements: missing nuclear correlations?

Shell model small matrix elements: Small configuration space?

Javier Menéndez (JSPS / U. Tokyo) 0$\nu\beta\beta$ decay nuclear matrix elements Thessaloniki, 2 September ’16
For $^{48}\text{Ca}$, enlarge configuration space from $pf$ to $sdpf$ (4 to 7 orbitals) increases matrix elements but only moderately 30%.

Iwata et al. PRL116 112502 (2016)

The contributions dominated by pairing (2p-2h) excitations enhance the $\beta\beta$ matrix element, but the contributions dominated by 1p-1h excitations suppress the $\beta\beta$ matrix element.

Shell model Monte Carlo calculations for heavier nuclei under way.
Correlations and $0\nu\beta\beta$ decay

$0\nu\beta\beta$ decay sensitive to pairing, quadrupole correlations

Maximum between superfluid nuclei, reduced with broken like-particle pairs or with proton-neutron pairs

Reduced if different deformation in mother and daughter nuclei

Caurier et al. PRL100 052503 (2008)

Rodríguez, Martínez-Pinedo PRL105 252503 (2010)
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 neglected
Shell model and GCM agree if proton-neutron correlations included

Related to approximate $SU(4)$ symmetry of the $\sum H(r)\sigma_i\sigma_j\tau_i\tau_j$ operator
Weak interactions: hadronic 1b+2b currents

Single-$\beta$ and $\beta\beta$ decay: $H_W = \frac{G_F}{\sqrt{2}} \left( j_{L\mu} J_L^{\mu\dagger} \right) + H.c.$

In nuclei (non-relativistic): $\langle \mathcal{N}_F | \sum_i g_V \tau_i^- + g_A \sigma_i \tau_i^- | \mathcal{N}_I \rangle$
corresponding to Fermi and Gamow-Teller transitions

Include $J_L^{\mu\dagger}$ 1b and 2b currents (operators) from chiral EFT
reflect strong interactions between nucleons in nuclei

Normal-ordered long-range two-body currents modify Gamow-Teller operator

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

$p$ independent $p$ dependent
2b currents in medium-mass nuclei

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

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

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 \( p \sim m_\pi \)
Nuclear matrix elements with 1b+2b currents

$\beta\beta$ decay nuclear matrix elements

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

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

Smaller quenching $q = 0.96...0.92$  Ekström et al. PRL113 262504 (2014)
Coupled-Cluster study of $^{14}$C, $^{22,24}$O, Hartree-Fock normal-ordering

Systematic calculations in light nuclei under way

Javier Menéndez (JSPS / U. Tokyo)
Summary

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

- Matrix element differences between present calculations, factor 2 − 3
- New $^{48}$Ca shell model result $\sim 30\%$ increase
  Shell model Monte Carlo underway
- Include isoscalar pairing correlations in EDF-type approaches
- Phenomenological matrix elements, ab initio calculations on the way, allow estimation of theoretical uncertainties
- $2\nu$ currents modify (reduce) matrix elements, but it remains to be settled to what extent: ab initio calculations in lighter (toy) systems
Collaborators

T. Otsuka
T. Abe

T. Abe

Y. Utsuno

Y. Utsuno

M. Honma

M. Honma

K. Hebeler,
G. Martínez-Pinedo
A. Schwenk, Simonis

J. D. Holt
D. Gazit

A. Poves
T. R. Rodríguez

J. Engel

E. Caurier
F. Nowacki

N. Hinohara

N. Hinohara