Recent progress on neutrinoless $\beta\beta$ decay nuclear matrix elements

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Workshop on “Double Beta Decay and Underground Science"
Waikoloa, 21th October 2018

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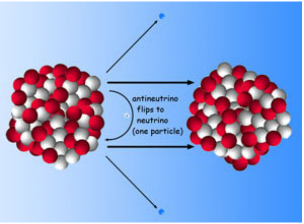
THE UNIVERSITY OF TOKYO

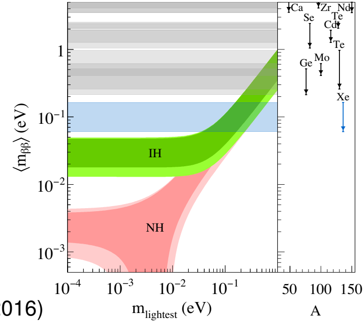
科研費
KAKENHI

Nuclear matrix elements for new physics searches

Neutrinos, dark matter studied in experiments using nuclei

Nuclear matrix elements depend on nuclear structure crucial to anticipate reach and fully exploit experiments





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

Dark matter: $\frac{d\sigma_{\chi\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$

$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor

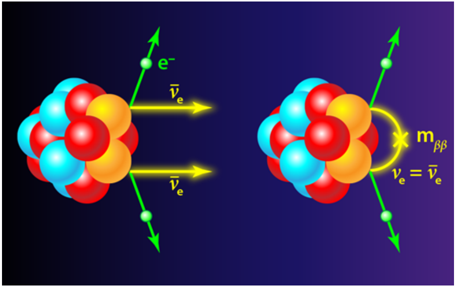
KamLAND-Zen, PRL117 082503(2016)

Calculating nuclear matrix elements

Nuclear matrix elements needed in low-energy new physics searches

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

- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  GFMC, Coupled-cluster, IM-SRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD

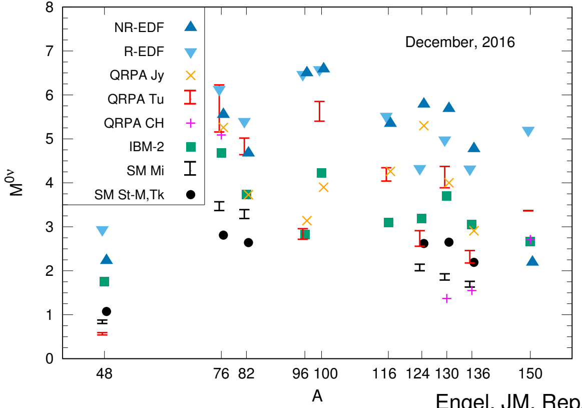


$0\nu\beta\beta$ decay nuclear matrix elements

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

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

Ω^X = Fermi ($\mathbb{1}$), GT ($\sigma_n \sigma_m$),Tensor
$H(r)$ = neutrino potential



Engel, JM, Rep. Prog. Phys. 80 046301 (2017)

How can nuclear matrix elements calculations improve?

How can nuclear structure experiments guide $0\nu\beta\beta$ decay?

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

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

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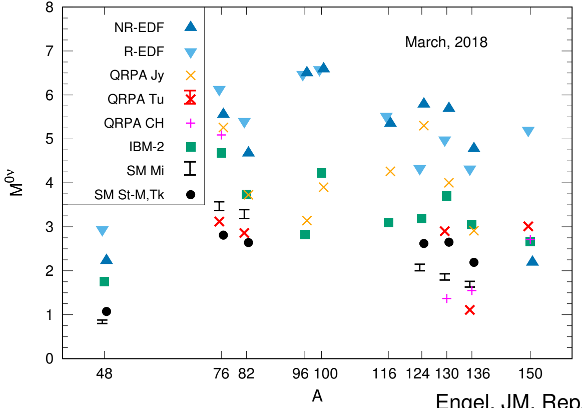


Engel, JM, Rep. Prog. Phys. 80 046301 (2017)

How can nuclear matrix elements calculations improve?

How can nuclear structure experiments guide $0\nu\beta\beta$ decay?

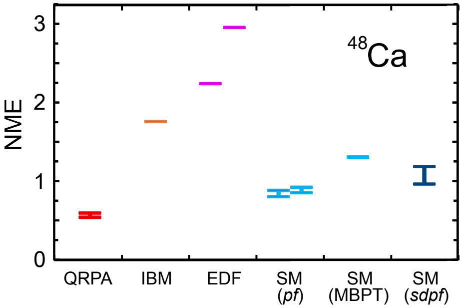
Fang et al. PRC97 045503(2018)

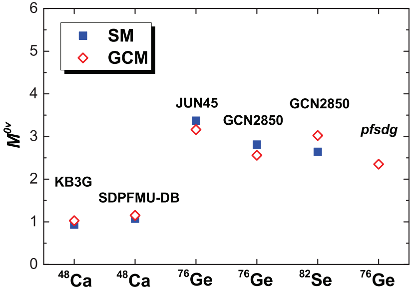
Shell model matrix elements in two shells

^{48}Ca$\rightarrow$^{48}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}Ca off by 1.3MeV in *pf* shell





Nuclear matrix element increases moderately 30%

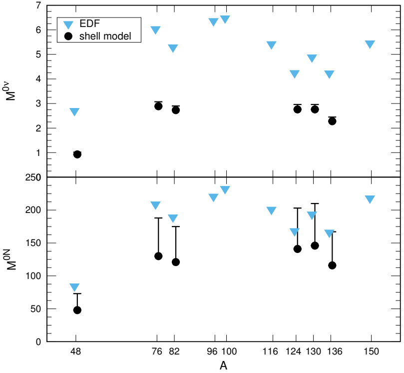
Iwata et al. PRL116 112502 (2016)

Likewise, very mild effect found in GCM calculations of ^{76}Ge

Jiao et al. PRC96 054310 (2017)

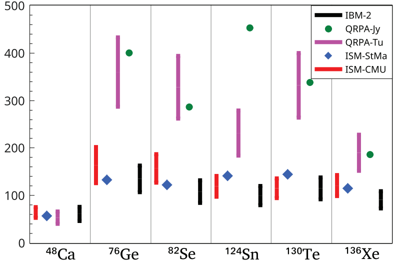
Heavy-neutrino exchange nuclear matrix elements

Contrary to light-neutrino-exchange, for heavy-neutrino-exchange decay shell model, IBM, and EDF matrix elements agree reasonably!



Song et al. PRC95 024305 (2017)

JM, JPG 45 014003 (2018)



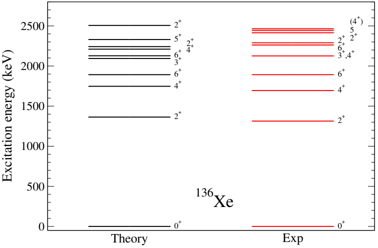
Neacsu et al. PRC100 052503 (2015)

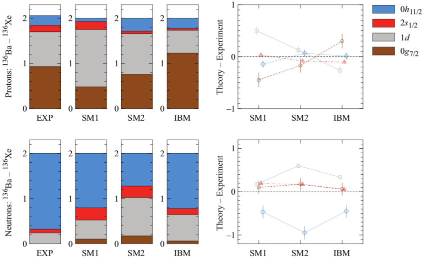
In general, nuclear matrix elements can be expressed in terms of Light and Heavy ν exchange ones

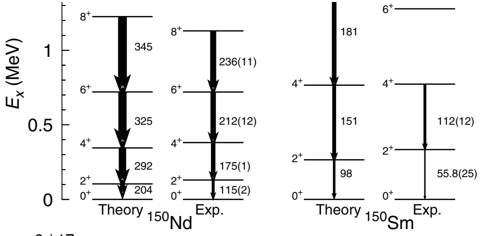
Cirigliano et al. JHEP 12 082 (2017)

Tests of nuclear structure

Spectroscopy well described: masses, spectra, transitions, knockout...







Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

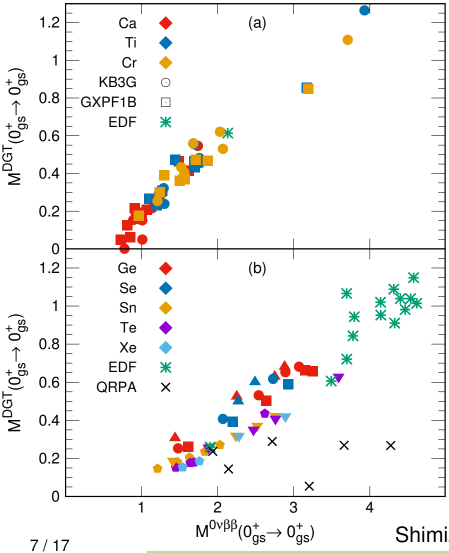
Szwec et al., PRC94 054314 (2016)

Rodríguez et al. PRL105 252503 (2010)

...

Vietze et al. PRD91 043520 (2015)

DGT and $0\nu\beta\beta$: heavy nuclei and $\beta\beta$ emitters



DGT transition to ground state very good linear correlation with $0\nu\beta\beta$ matrix elements

$\Rightarrow$

DGT explored @RIKEN, INFN can give insight to $0\nu\beta\beta$ decay

Correlation across nuclear chart from Ca to Ge and Xe

Common to nuclear shell model energy-density functional theory and interacting boson model

$0 \lesssim M^{0\nu\beta\beta} \lesssim 5$

disagreement to QRPA

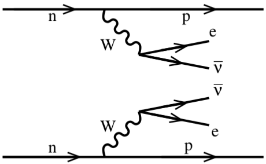
Shimizu, JM, Yako, PRL120 142502 (2018)

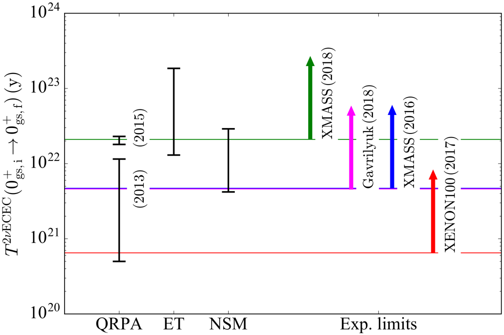
Two-neutrino $\beta\beta$ decay and ECEC

Test of $0\nu\beta\beta$ decay: comparison of predicted $2\nu\beta\beta$ decay vs data

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

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



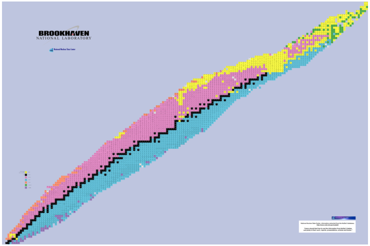


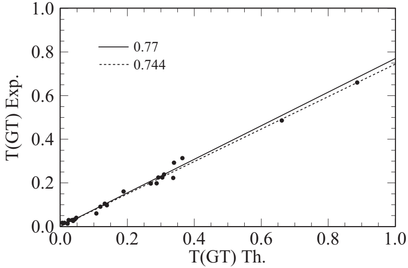
Coello Pérez, JM, Schwenk, arXiv:1809.04443

Shell model, QRPA and Effective theory predictions of ^{124}Xe 2νECEC suggest experimental detection in near future

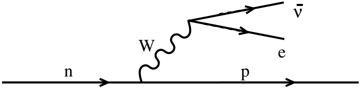
β decays

β decays (e^- capture) main decay model along nuclear chart
In general well described by nuclear structure theory: shell model...





Martinez-Pinedo et al. PRC53 2602(1996)



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

Gamow-Teller transitions:
theory needs $\boldsymbol{\sigma}_i \tau$ “quenching"

Ab initio many-body methods

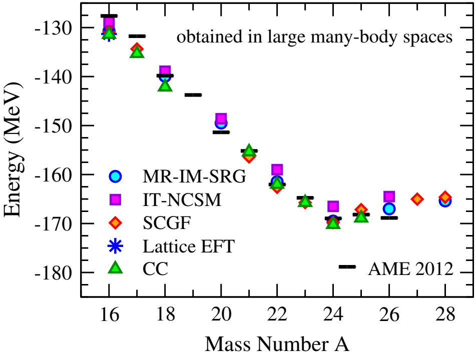
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

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)

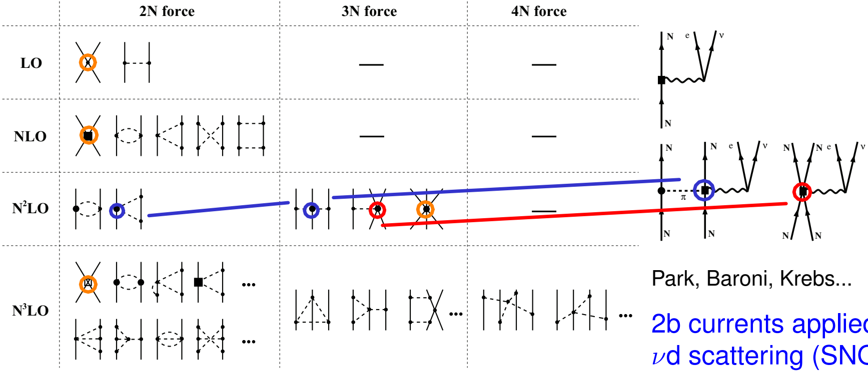


Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



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

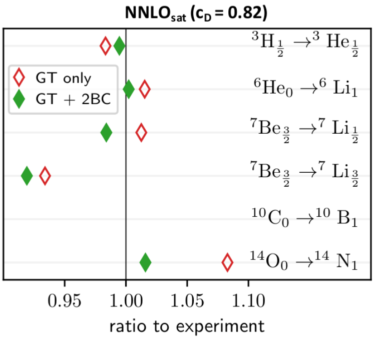
Park, Baroni, Krebs...

2b currents applied to νd scattering (SNO), ^{3}H β-decay, μ moment...

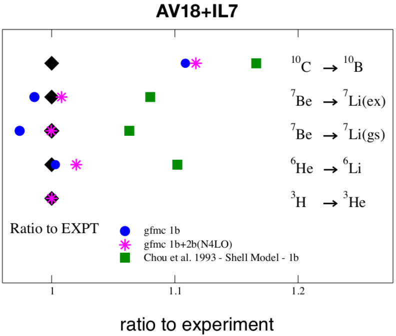
β decay in very light nuclei: GFMC vs NCSM

Quantum Monte Carlo, No Core Shell Model β decays in $A \leq 10$

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



No-core shell model



Quantum Monte Carlo

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

Impact of 2b currents small (few %), disagreement on sign

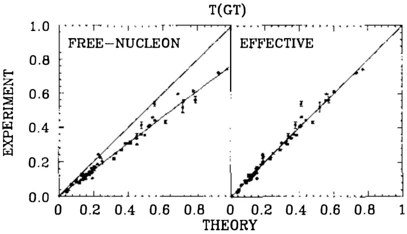
β decay in medium-mass nuclei: IMSRG

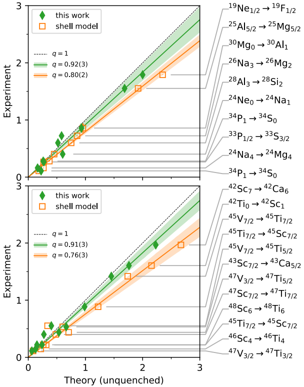
TRIUMF "Quenching" of g_A in Gamow-Teller Decays

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

Minor effect from consistent effective operator

Significant effect from neglected 2-body currents



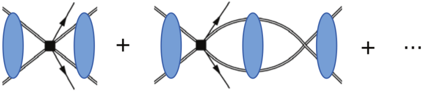


Ab initio calculations explain data with unquenched g_A

From J. Holt, INT-18-1a program

Open questions: contact operator, $\beta\beta$ 2b currents

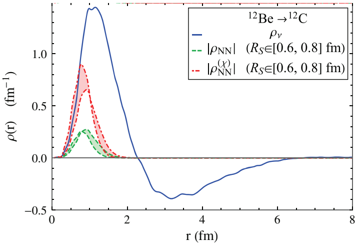
Contact light-neutrino operator



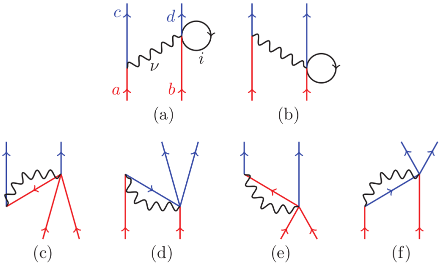
Cirigliano et al. PRL120 202001(2018)

Unknown coupling value

Short-range character



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



Estimated effect $\sim$ 10%

Wang et al. PRC98 031301 (2018)

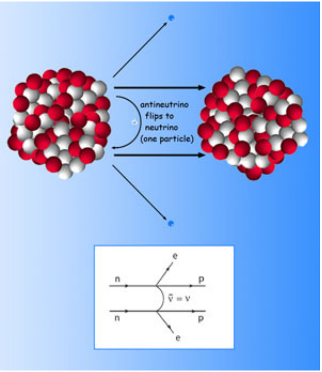
compared to $\sim$ 20%
in β decay ("quenching")

JM et al. PRL107 062501(2011)

Summary

Nuclear matrix elements are key
for the design of next-generation tonne-scale $0\nu\beta\beta$ decay experiments
and for fully exploiting the experimental results

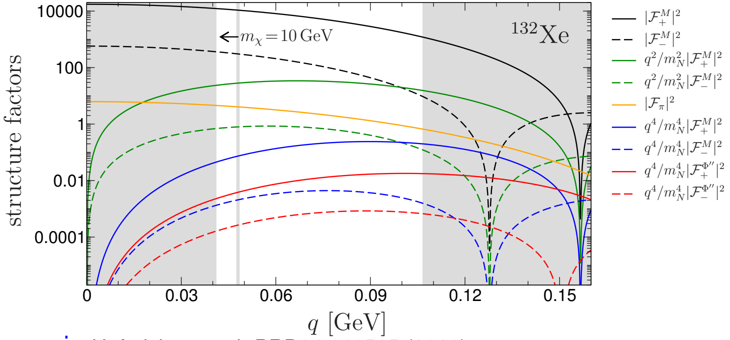
- Present matrix element calculations disagree
  suggested convergence of QRPA results
  Need improved calculations,
  guidance from other nuclear experiments
- Ab initio calculations in light nuclei
  solve much of β decay “quenching" problem
  ab initio matrix elements in $\beta\beta$ emitters soon!
- Double GT transitions, ^{124}Xe $2\nu\beta\beta$ decay,
  pursued in RIKEN, INFN, XMASS, XENON
  promising insight on $0\nu\beta\beta$ matrix elements



Nuclear structure factors for dark matter scattering

Cross section depends on nuclear structure factors $\mathcal{F}$:
spin-independent (SI), spin-dependent (SD), coherent pion coupling...

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



For xenon in Hoferichter et al. PRD94 063505 (2016)

For argon, fluorine, germanium... very soon in the arXiv, stay tuned!

Collaborators

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