Towards reliable $\beta\beta$ decay matrix elements with uncertainties

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Post K-computer project "Elucidation of the Fundamental Laws and Evolution of the Universe"

First Tsukuba-CCS-RIKEN joint workshop on
"Microscopic theories of nuclear structure and dynamics"
Center for Computational Studies, Tsukuba University,
15th December 2016

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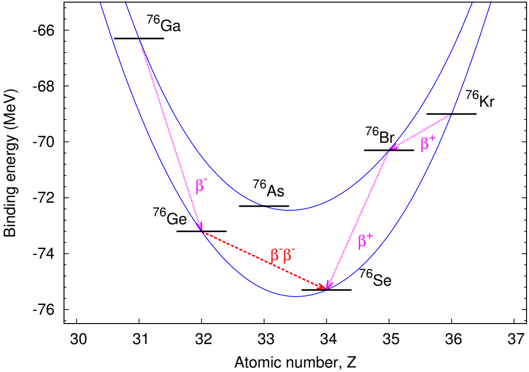
Center for Nuclear Study (CNS)

東京大学
THE UNIVERSITY OF TOKYO

Double-beta decay

$\beta\beta$ decay is a second-order process,
only to be observed when single-β decay is forbidden or suppressed



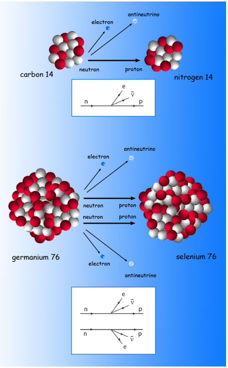
Transition	Experiment
^{48}Ca $\rightarrow$ ^{48}Ti	CANDLES
^{76}Ge $\rightarrow$ ^{76}Se	GERDA, MAJORANA
^{82}Se $\rightarrow$ ^{82}Kr	SuperNEMO
^{96}Zr $\rightarrow$ ^{96}Mo	
^{100}Mo $\rightarrow$ ^{100}Ru	AMoRE
^{110}Pd $\rightarrow$ ^{110}Cd	
^{116}Cd $\rightarrow$ ^{116}Sn	COBRA
^{124}Sn $\rightarrow$ ^{124}Te	
^{130}Te $\rightarrow$ ^{130}Xe	CUORE, SNO+
^{136}Xe $\rightarrow$ ^{136}Ba	EXO, KamLAND-Zen, NEXT
^{150}Nd $\rightarrow$ ^{150}Sm	

Only dozen promising candidates for detection, very long lifetimes
Present half-life limits in ^{76}Ge, ^{136}Xe set to $T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y, 10^{26} y!

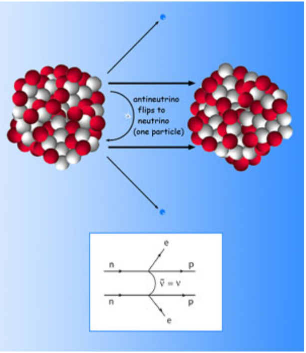
Lepton-number conservation

Lepton number is conserved in all physical processes observed to date

Uncharged massive particles like Majorana neutrinos (ν) theoretically allow lepton number violation



β decay, $\beta\beta$ decay...

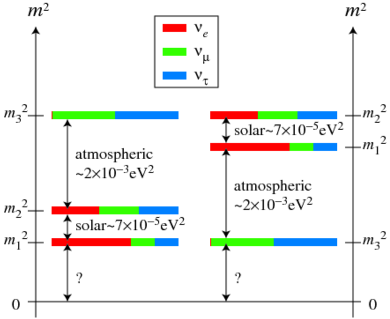


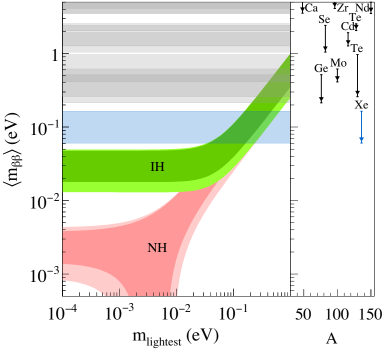
Neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay

Neutrino mass hierarchy

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

sensitive to absolute neutrino masses, $m_{\beta\beta} = \left|\sum U_{ek}^2 m_k\right|$, and hierarchy



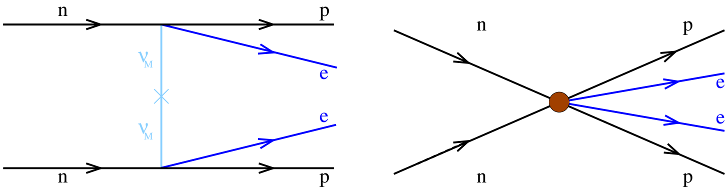


KamLAND-Zen: PRL117 082503(2016)

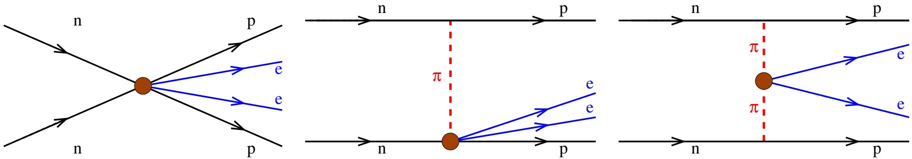
Matrix elements needed to make sure next generation ton-scale experiments fully explore "inverted hierarchy"

$0\nu\beta\beta$ decay and new physics

Neutrinoless $\beta\beta$ decay can also be mediated by the exchange of a (not discovered) heavy-particle Barea, Horoi, Menéndez, Šimkovic, Suhonen...



Heavy-particle exchange: long-range pion exchanges dominate using effective field theory (EFT) arguments Prezeau et al. PRD68 034016(2003)
short-range diagrams additionally suppressed: nucleons $\sim$ 1 fm away



Couplings need input from Lattice QCD Nicholson et al. arXiv:1608.04793

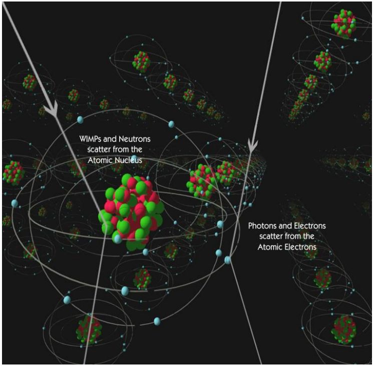
Nuclear matrix elements

The Nuclear Matrix Element of the process has to be evaluated

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

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

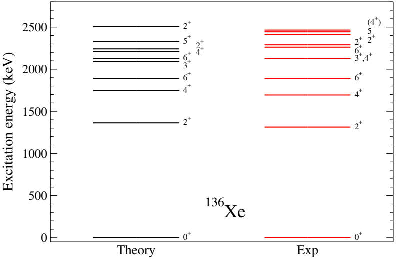
Description of the
lepton-nucleus interaction:
Evaluation (non-perturbative)
of the hadronic currents inside nucleus:
phenomenological, effective theory

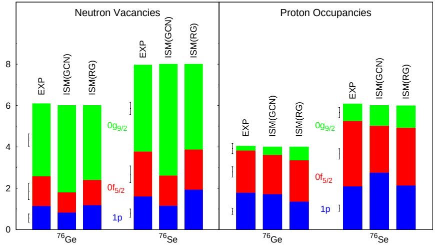


CDMS Collaboration

Test of nuclear structure

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

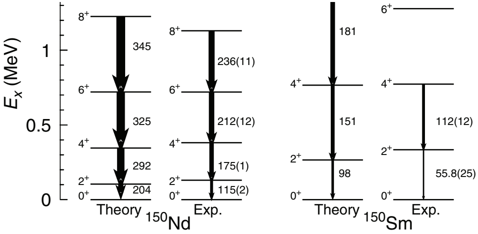




Shell model:

JM, Caurier, Nowacki, Poves

PRC80 048501 (2009)



Energy Density Functional:

Rodríguez, Martínez-Pinedo

PRL105 252503 (2010)

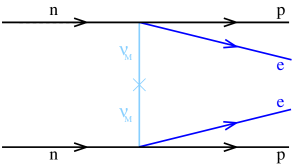
Neutrinoless $\beta\beta$ decay operator

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
- Ω^X is the spin structure:
  Fermi ($\mathbb{1}$), Gamow-Teller ($\sigma_n \sigma_m$), Tensor $\left[Y^2(\hat{r}) \left[\sigma_n \sigma_m\right]^2 \right]^0$
- $H(r)$ is the neutrino potential, depends on m_ν

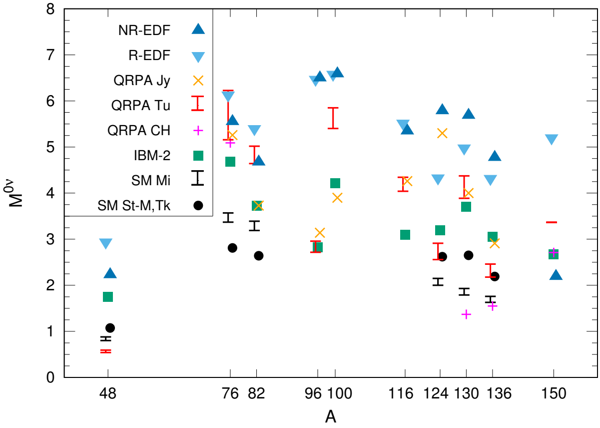
$$H^X(r) = \frac{2}{\pi} \frac{R}{g_A^2(0)} \int_0^\infty f^X(pr) \frac{h^X(p^2)}{\left(\sqrt{p^2+m_\nu^2}\right)\left(\sqrt{p^2+m_\nu^2} + \langle E^m \rangle - \frac{1}{2}(E_i - E_f)\right)} p^2\, dp \sim \frac{R}{r}$$

Closure approximation typically used
tested to be valid to $\sim 10\%$
Muto NPA577 415C(1994)
Sen'kov et al. PRC90 051301(2014)



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

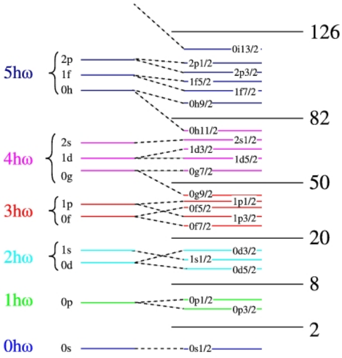
Large difference in nuclear matrix element calculations: factor $\sim 2-3$



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

Shell model small matrix elements: small configuration space?

Shell model (configuration interaction)



Solve the many-body problem "exactly" around the Fermi surface

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

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

$$H\,|\Psi\rangle = E\,|\Psi\rangle \;\rightarrow H_{eff}\,|\Psi\rangle_{eff} = E\,|\Psi\rangle_{eff}$$

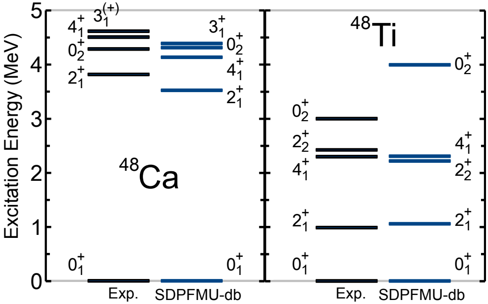
$$|\Psi\rangle_{eff} = \sum_{\alpha} c_\alpha\,|\phi_\alpha\rangle\,, \quad |\phi_\alpha\rangle = a^+_{i1}a^+_{i2}...a^+_{iA}\,|0\rangle$$

Exact diagonalization: 10^{11} dimension Caurier et al. RMP77 427 (2005)

Monte Carlo shell model: 10^{23} dimension Togashi et al. arXiv:1606.09056

Shell model configuration space: spectra

For ^{48}Ca enlarge shell model configuration space
from *pf* to *sdpf* (4 to 7 orbitals) restricted to $2\hbar\omega$ excitations
dimension of ^{48}Ti calculation increases from less than 10^6 to over 10^9



Iwata et al. PRL116 112502 (2016)

The 0^+_2 state in ^{48}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}Ca 0^+_2)

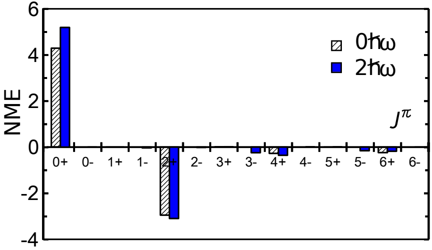
The difference in the ^{48}Ca two-neutrino $\beta\beta$ decay matrix element
is about 5% between *pf* and *sdpf* calculations

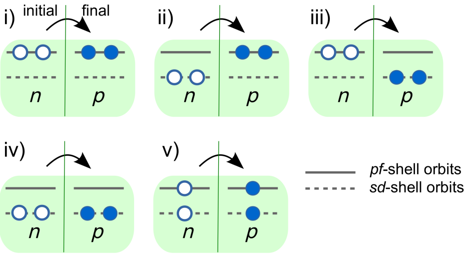
Shell model configuration space: $\beta\beta$ decay

Nuclear matrix element decomposition in terms of J^P of decaying neutron pair

Pairs dominate matrix element remaining J^P contributions cancel leading contribution

Vogel, Engel, Šimkovic, Suhonen, Poves...





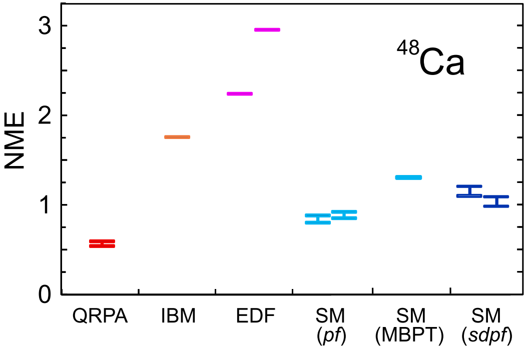
The contributions dominated by pairing (2p-2h) excitations enhance the $\beta\beta$ matrix element, but the contributions dominated by 1p-1h excitations suppress the $\beta\beta$ matrix element

Iwata et al. PRL116 112502 (2016)

Similar competition expected in other $\beta\beta$ decays

Shell model configuration space: $\beta\beta$ matrix element

From *pf* to *sdpf* nuclear matrix element enhanced only moderately $\sim$ 30%



Iwata et al. PRL116 112502 (2016)

sdpf matrix element close to many-body perturbation theory based on *pf*-shell calculation

Shell model matrix element still much smaller than other approaches

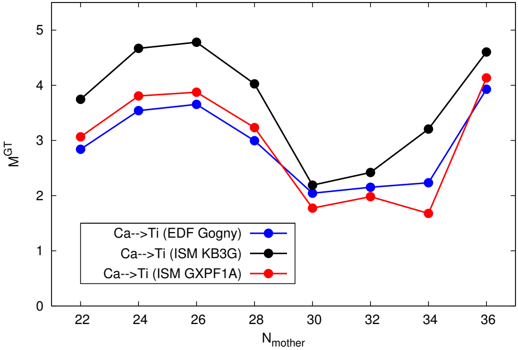
Theoretical uncertainty by using different interactions $\sim$ 20%, similar to different *pf*-shell interactions

Similar enlarged configuration space calculations in progress with Monte Carlo shell model in ^{76}Ge, ^{82}Se, ^{96}Zr...

$0\nu\beta\beta$ 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)

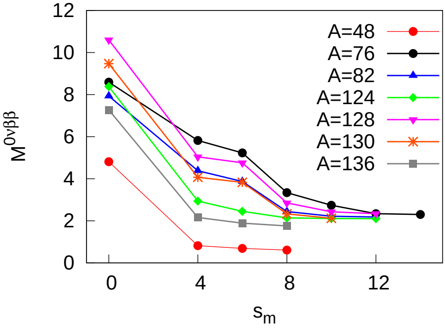
NME follows generalized seniority model:

$$M^{0\nu\beta\beta}_{GT} \simeq \alpha_\pi \alpha_\nu \sqrt{N_\pi + 1}\sqrt{\Omega_\pi - N_\pi}\sqrt{N_\nu}\sqrt{\Omega_\nu - N_\nu + 1},$$ Barea, Iachello PRC79 044301(2009)

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

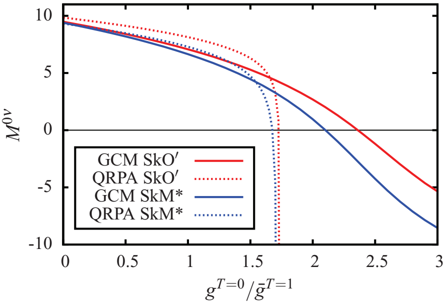
$0\nu\beta\beta$ decay favoured by (isovector) pairing, disfavored by isoscalar pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

Addition of isoscalar pairing reduces matrix elements



Hinohara, Engel PRC90 031301 (2014)

Related to approximate $SU(4)$ symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator

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

Separable collective interaction from shell model Hamiltonian KB3G

Dufour, Zuker PRC54 1653(1996)

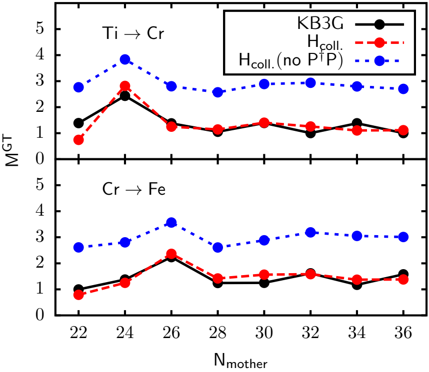
Monopole part: from KB3G

Multipole part:
Diagonalize interaction in paring,
particle-hole representations
for each J, π

Large eigenvalues
fix collective strenghts:
isovector/isoscalar pairing, quadrupole...

$$H_{\text{coll}} = H_M + g^{T=1} \sum_{n=-1}^{1} S_n^\dagger S_n + g^{T=0} \sum_{m=-1}^{1} P_m^\dagger P_m$$

$$+ g_{ph} \sum_{m,n=-1}^{1} : \mathcal{F}_{mn}^\dagger \mathcal{F}_{mn} : + \chi \sum_{\mu=-2}^{2} : Q_\mu^\dagger Q_\mu :$$



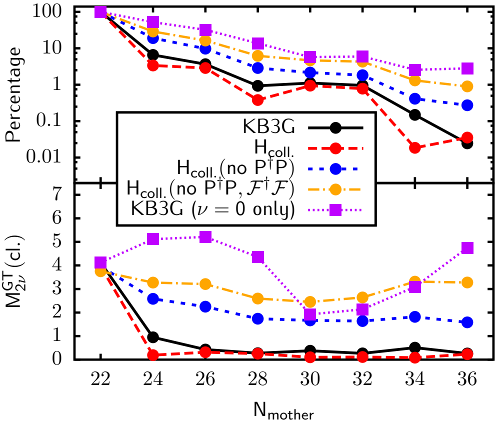
JM et al. PRC93 014305 (2016)

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

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

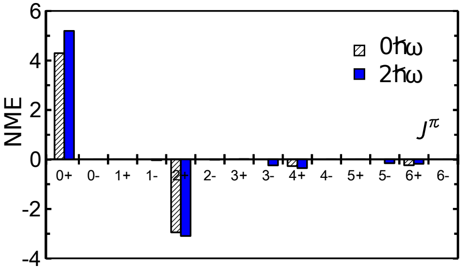


Missing correlations breaking SU(4) symmetry, strongly impact $\beta\beta$ decay

Pairing correlations and light/heavy-neutrino exchange

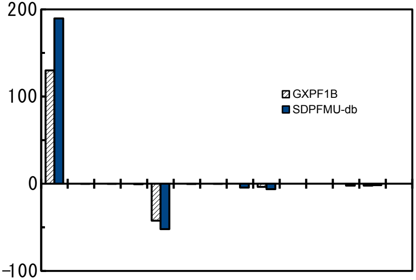
$0\nu\beta\beta$ decay matrix element from *sd*-shell to *sdpf* space ($2\hbar\omega$)
increases more in heavy-neutrino exchange (short-range transition)
enhancement due to pairing correlations ($J = 0$ pairs)

Light-neutrino exchange



Iwata et al. PRL 116, 112502 (2016)

Heavy-neutrino exchange

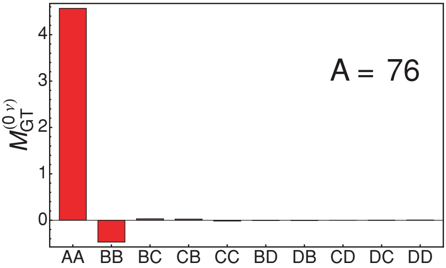


Deficiencies in shell model due to missing pairing correlations
may be more apparent in heavy-neutrino exchange

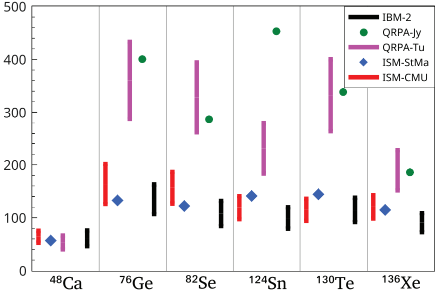
IBM matrix elements and heavy-neutrino exchange

Pairing ($J = 0$) similar in shell model and IBM calculations
but cancellation due to $J = 2$ pairs missing in IBM:
similar to shell model heavy-neutrino exchange

Contrary to light-neutrino exchange
shell model and IBM agree for heavy-neutrino exchange $\beta\beta$ decay!



Barea et al. PRC 79, 044301 (2009)

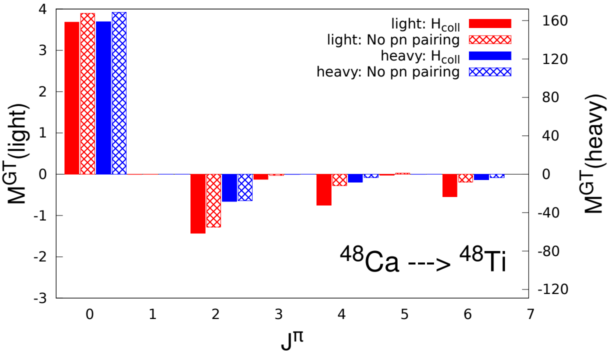


Neacsu et al. PRC100 052503 (2015)

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

Isoscalar pairing correlations less important in heavy-neutrino exchange

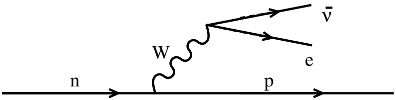
If isoscapar pairing is missing in IBM and EDF calculations
heavy-neutrino exchange matrix elements should be closer to shell model



Probably more physics correlations missing: quadrupole pairing...

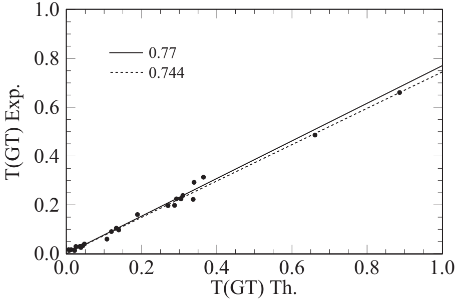
Gamow-Teller transitions: "quenching"

Single-β decays well described by nuclear structure (shell model)



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

$$g_A^{\text{eff}} = q g_A, \quad q \sim 0.7 - 0.8.$$



Theory needs to “quench“ $\sigma\tau$ operator to predict Gamow-Teller lifetimes

This puzzle has been the target of many theoretical efforts:

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

Anything missing in the many-body approach?

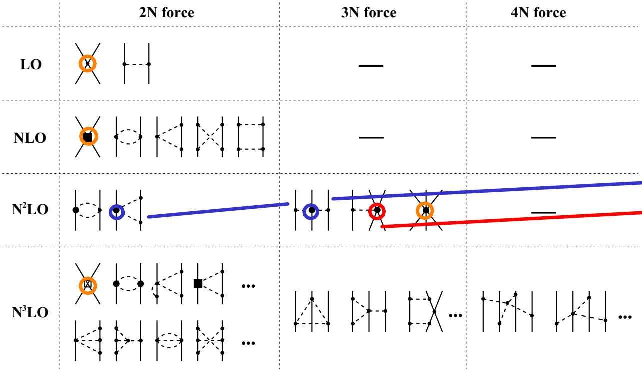
Anything missing in the transition operator?

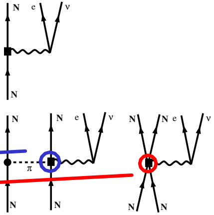
Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



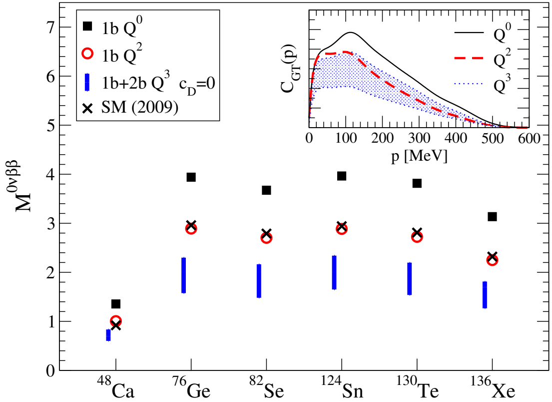


Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...

Park, Gazit, Klos, Baroni...

Short-range couplings fitted to experiment once

Nuclear matrix elements with 1b+2b currents

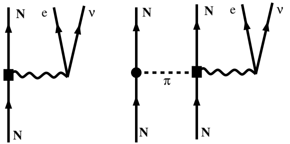


JM, Gazit, Schwenk PRL107 062501 (2011)

JM arXiv:1605.05059, updated 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 $\sim 20\% - 50\%$

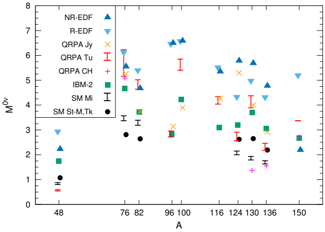
Smaller quenching $q = 0.96...0.92$ Ekström et al. PRL113 262504 (2014)

Coupled-Cluster study of ^{14}C, $^{22,24}O$, Hartree-Fock normal-ordering

Towards theoretical uncertainties

Only a small *part of* the statistical uncertainties of matrix element calculations have been estimated:

- effect of different nuclear interactions: shell model, EDF Gogny/relativistic, QRPA...
- model parameters: g_{pp} (QRPA), g_A...
- c_i couplings in 2b current contributions



These statistical effects should be explored systematically

- correlations to other observables:
  single-β and two-neutrino $\beta\beta$ decays
  Gamow-Teller strenghts, excitation spectra, two-neutron transfer...

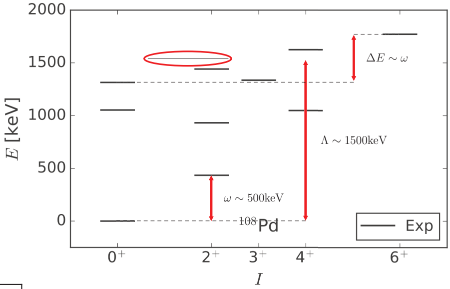
Systematic uncertainties much harder to estimate
benchmark to ab initio calculations, controlled approximations

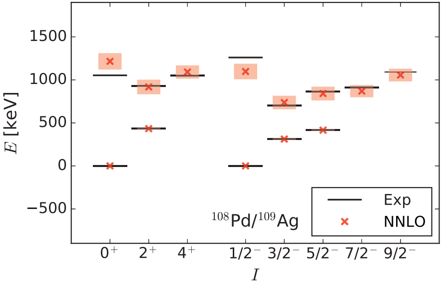
Effective field theory for β decay

In spherical nuclei,
as typical $\beta\beta$ emitters,
develop an effective field theory
based on phonon excitations,
expansion in breakdown scale

Coello Pérez, Papenbrock

PRC92 064309('15), PRC94 054316('16)





Once EFT couplings are fixed,
predictions with uncertainties

Excitation spectra,
electromagnetic transitions

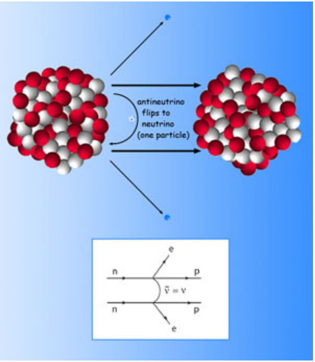
Extend to β and $\beta\beta$ decays:
matrix elements
with estimated uncertainties

Coello Pérez et al., in progress

Summary

Neutrinoless double-beta decay nuclear matrix elements
key to fully exploit next generation experiments testing inverted hierarchy

- Matrix element differences
  between present calculations, factor $2 - 3$
- New ^{48}Ca shell model result 30% increase,
  shell model Monte Carlo underway
- Include isoscalar pairing correlations
  in EDF-type and IBM approaches
- Understand g_A quenching?
  2b currents reduce matrix elements,
  further reduction due to many-body methods?
- Estimation of theoretical uncertainties:
  parameter variation and correlations
  effective field theory approach
  ab initio calculations



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