Neutrinoless $\beta\beta$ decay matrix elements: present and future

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Nuclear physics and neutrinoless $\beta\beta$ decay

Neutrinos, dark matter studied in experiments using nuclei

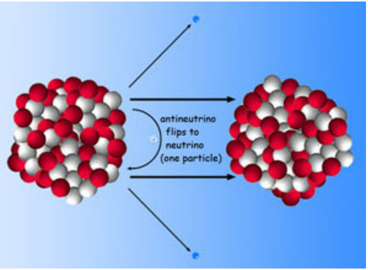
Nuclear matrix elements depend on nuclear structure crucial to anticipate reach and fully exploit experiments

$0\nu\beta\beta$ 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: $\frac{d\sigma_{\chi\mathcal{N}}}{d\mathbf{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$

$M^{0\nu\beta\beta}$: Nuclear matrix element

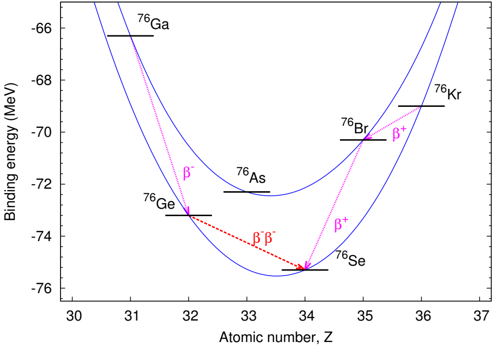
$\mathcal{F}_i$: Nuclear structure factor



Neutrinoless $\beta\beta$ decay

Lepton-number violation, Majorana nature of neutrinos

Second order process only observable in rare cases with β-decay energetically forbidden or hindered by ΔJ

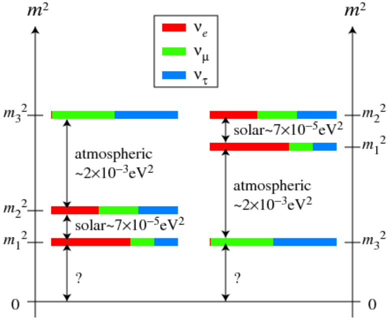


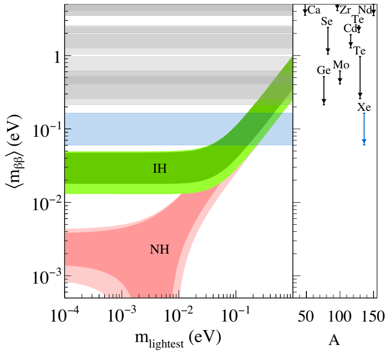
Best limit: ^{76}Ge (GERDA), ^{130}Te (CUORE), ^{136}Xe (EXO, KamLAND-Zen)

Next generation experiments: inverted hierarchy

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

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





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

KamLAND-Zen, PRL117 082503(2016)

Outline

Present status of $0\nu\beta\beta$ decay nuclear matrix elements

Future prospects for $0\nu\beta\beta$ nuclear matrix element calculations

Can nuclear structure experiments help with $0\nu\beta\beta$ decay?

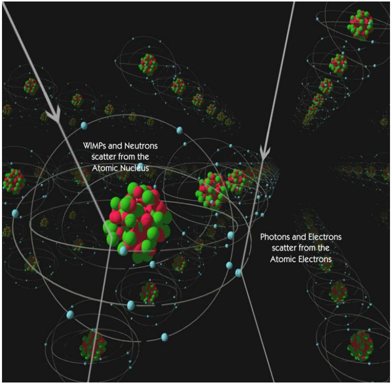
Calculating nuclear matrix elements

Nuclear matrix elements needed to study fundamental symmetries

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

- Nuclear structure calculation of the initial and final states:
  Shell model Retamosa, Poves, JM, Horoi...
  Energy-density functional Rodríguez, Yao...
  QRPA Vogel, Faessler, Šimkovic, Suhonen...
  Interacting boson model Iachello, Barea...
  Ab initio many-body methods
  Green's Function MC, Coupled-cluster, IM-SRG...

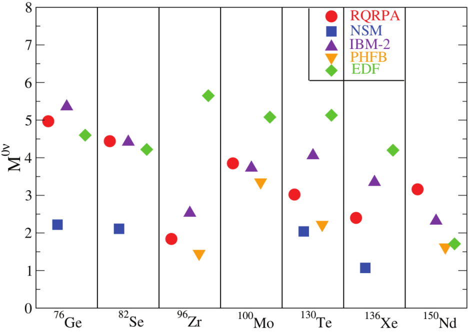
- Lepton-nucleus interaction:
  Study hadronic current in nucleus: phenomenological approaches, effective theory of QCD



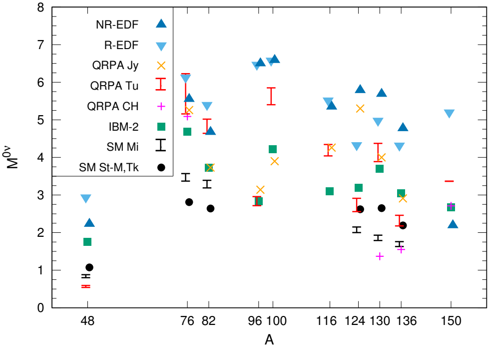
CDMS Collaboration

$0\nu\beta\beta$ nuclear matrix elements: last 5 years

Comparison of nuclear matrix element calculations: 2012 vs 2017



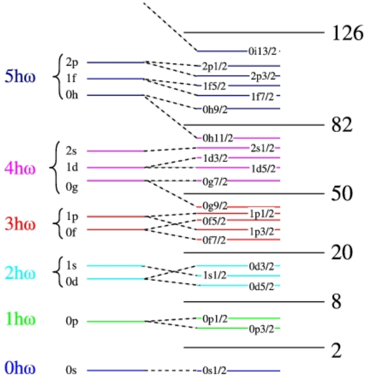
Vogel, J. Phys. G 39 124002 (2012)



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

What have we learned in the last 5 years?

Configuration space



Nuclear shell model configuration space only keep essential degrees of freedom

- High-energy orbits: always empty
- Configuration space: where many-body problem is solved
- Inert core: always filled

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

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

Shell model codes (1 major oscillator shell) $\sim 10^{10}$ Slater dets. Caurier et al. RMP77 (2005)

QRPA calculations suggest larger spaces ($\gtrsim$ 2 major shells) needed

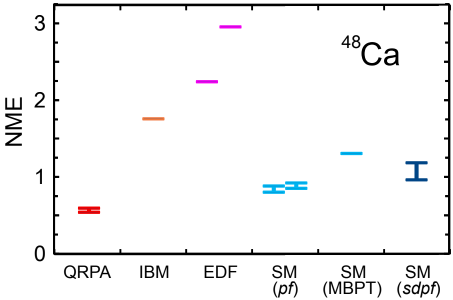
Dimension $\sim$

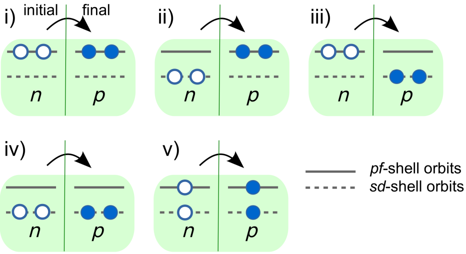
$$\binom{(p+1)(p+2)_\nu}{N}\binom{(p+1)(p+2)_\pi}{Z}$$

Shell model configuration space: two shells

For ^{48}Ca enlarge configuration space
from *pf* to *sdpf*
4 to 7 orbitals, dimension 10^5 to 10^9
increases matrix elements
but only moderately 30%

Iwata et al. PRL116 112502 (2016)



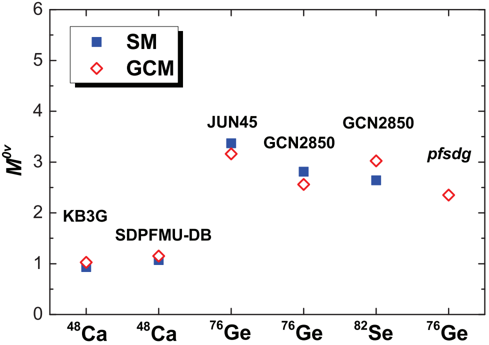


Contributions dominated by pairing
2 particle – 2 hole excitations
enhance the $\beta\beta$ matrix element,

Contributions dominated by
1 particle – 1 hole excitations
suppress the $\beta\beta$ matrix element

^{76}Ge matrix element in two shells

Large configuration space calculations in 2 major oscillator shells
Include all relevant correlations: isovector/isoscalar pairing, deformation
Many-body approach: generating coordinate method (GCM)



GCM approximates
shell model calculation

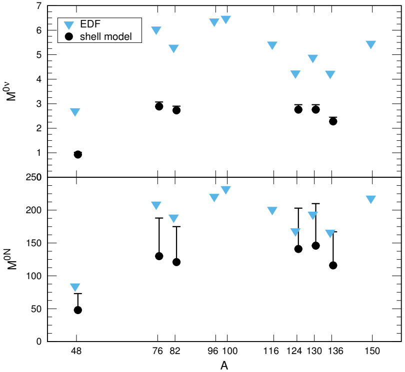
Degrees of freedom,
or generating coordinates,
validated against
exact shell model
in small configuration space

Jiao et al. PRC96 054310 (2017)

^{76}Ge nuclear matrix element in 2 major shells
very similar to shell model nuclear matrix element in 1 major shell

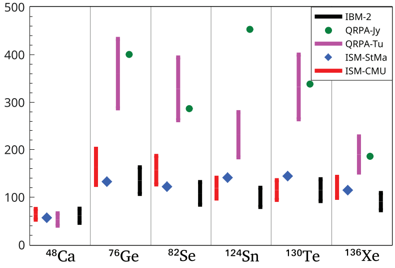
Heavy-neutrino exchange nuclear matrix elements

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 in print



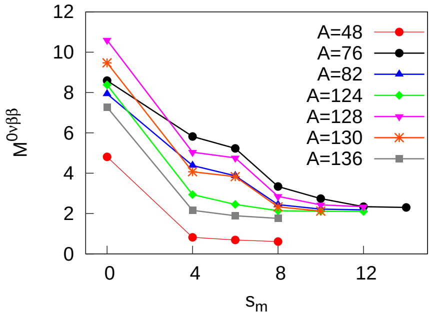
Neacsu et al. PRC100 052503 (2015)

Suggests differences in treating longer-range nuclear correlations dominant in light-neutrino exchange

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

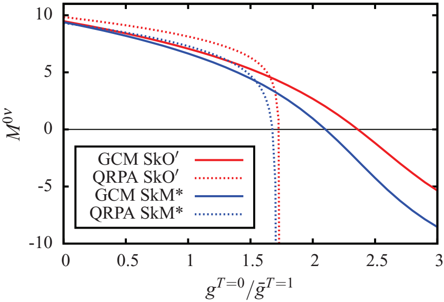
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing, but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

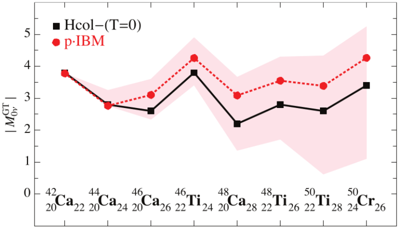
Addition of isoscalar pairing reduces matrix element value

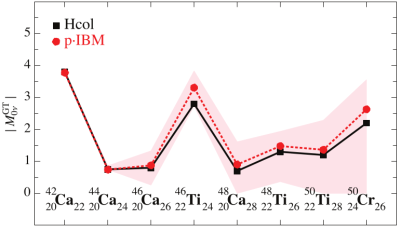


Hinohara, Engel PRC90 031301 (2014)

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

IBM matrix elements with proton-neutron pairing





van Isacker et al. arXiv:1708.05925

Energy-density functional (EDF) theory and interating boson model (IBM) calculated nuclear matrix elements do not include explicitly proton-neutron pairing correlations

This effect (partially) accounted for by other degrees of freedom present in these approaches

Include *p*-boson ($L = 1$) to IBM in addition to *s* and *d* bosons ($L = 0, 2$)

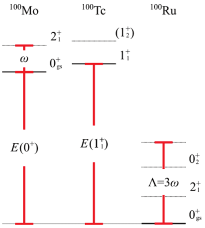
First IBM results in calcium region suggest nuclear matrix elements could be somewhat reduced

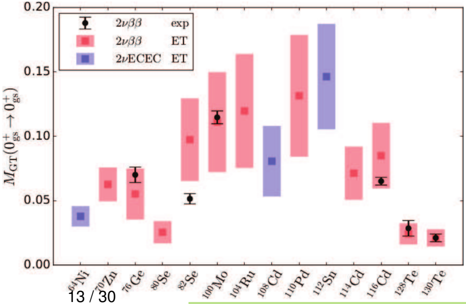
Matrix elements: theoretical uncertainty

Systematic uncertainty hard to estimate for phenomenological matrix elements

Effective theory for $\beta\beta$ decay: spherical core coupled to one nucleon

Couplings adjusted to experimental data, uncertainty given by effective theory (breakdown scale, systematic expansion)





Take β decay data to predict $2\nu\beta\beta$

$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \boldsymbol{\sigma}_n \tau_n^- \, | 1_k^+ \rangle \langle 1_k^+ | \sum_m \boldsymbol{\sigma}_m \tau_m^- \, | 0_i^+ \rangle}{E_k - (M_i + M_f)/2}$$

Good agreement with large errors (leading-order calculations)

Coello-Pérez, JM, Schwenk, arXiv:1708.06140

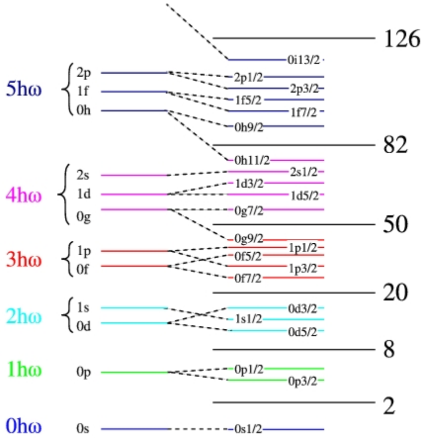
Outline

Present status of $0\nu\beta\beta$ decay nuclear matrix elements

Future prospects for $0\nu\beta\beta$ nuclear matrix element calculations

Can nuclear structure experiments help with $0\nu\beta\beta$ decay?

Ab initio methods: No core shell model



No core shell model

Many-body wave function
linear combination of
Slater Determinants
from single particle states in the basis
(3D harmonic oscillator)

$$|i\rangle = |n_i l_i j_i m_{j_i} m_{t_i}\rangle$$

$$|\phi_\alpha\rangle = a^+_{i1} a^+_{j2} \ldots a^+_{kA} |0\rangle$$

$$|\Psi\rangle = \sum_\alpha c_\alpha |\phi_\alpha\rangle$$

$$H|\Psi\rangle = E|\Psi\rangle$$

$$\text{Dim} \sim \binom{(p+1)(p+2)_\nu}{N} \binom{(p+1)(p+2)_\pi}{Z}$$

Dimensions increase
combinatorially...

Coupled Cluster, In-Medium SRG

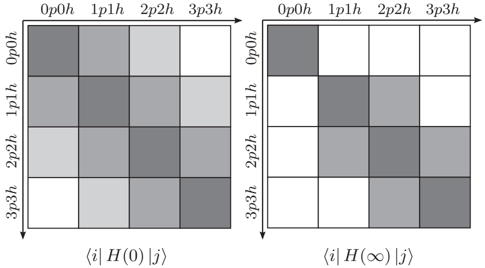
Coupled Cluster method: operators (correlations) acting on reference impose no particle-hole excitations present in the reference state

$$|\Psi\rangle = e^{-(T_1+T_2+T_3\cdots)}\,|\Phi\rangle$$

with $T_1 = \sum_{\alpha,\bar\alpha} t_{\alpha}^{\bar\alpha} \left\{a^\dagger_{\bar\alpha}, a_\alpha\right\}$, $T_2 = \sum_{\alpha\beta,\bar\alpha\bar\beta} t_{\alpha\beta}^{\bar\alpha\bar\beta} \left\{a^\dagger_{\bar\alpha} a^\dagger_{\bar\beta}, a_\alpha a_\beta\right\}$, $\cdots$

solve $\left\langle \Phi_{\alpha}^{\bar\alpha}\right| e^{\sum T_i} H e^{-\sum T_i}\,|\Phi\rangle = 0$, $\left\langle \Phi_{\alpha\beta}^{\bar\alpha\bar\beta}\right| e^{\sum T_i} H e^{-\sum T_i}\,|\Phi\rangle = 0$

In-medium similarity renormalization group method: apply a similarity (unitary) transformation to decouple reference state from particle-hole excitations



Ab initio many-body methods

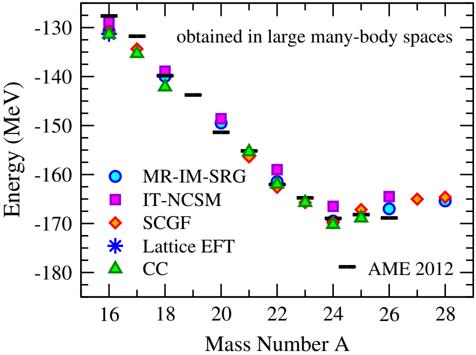
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

No-core shell model
(Importance-truncated)

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

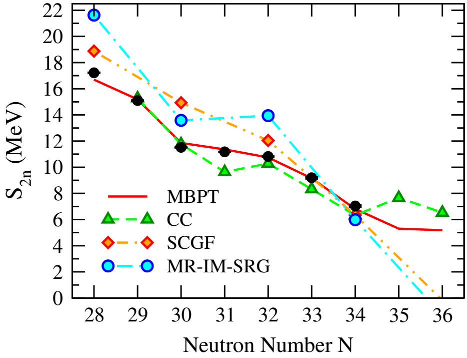
Self-consistent Green's function
Cipollone et al. PRL111 062501(2013)

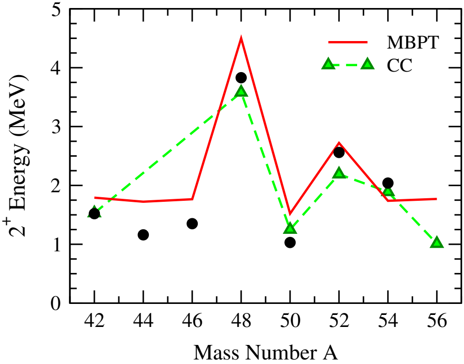
Coupled-clusters
Jansen et al. PRL113 142502(2014)



Calcium isotopes with NN+3N forces

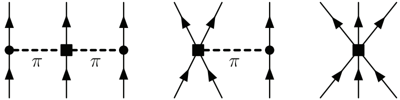
Calculations with NN+3N forces predict shell closures at ^{52}Ca, ^{54}Ca





$^{51-54}$Ca masses [TRIUMF/ISOLDE]

^{54}Ca 2_1^+ excitation energy [RIBF,RIKEN]



Hebeler et al. ARNPS 65 457 (2015)

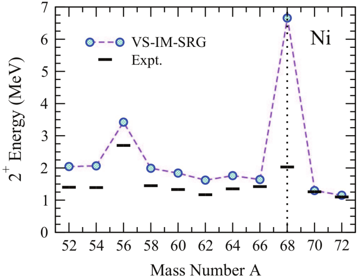
Ab initio $0\nu\beta\beta$ decay matrix elements?

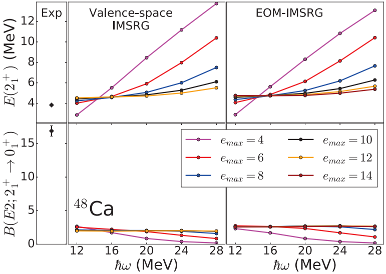
Nuclei up to $A \sim 70$
explored with ab initio approaches
Limited by good chiral nuclear force

Challenge for ab initio $0\nu\beta\beta$ decay:
(unitary) transformation: $H' = U^\dagger H U$
applied to operators: $O' = U^\dagger O U$
First electromagnetic transition results
$\Rightarrow$ $0\nu\beta\beta$ decay matrix elements next

^{48}Ca ab initio $0\nu\beta\beta$ decay
nuclear matrix element
ready very soon: stay tuned!

Simonis et al. PRC96 014303 (2017)
Parzuchowski et al. PRC96 034324 (2017)



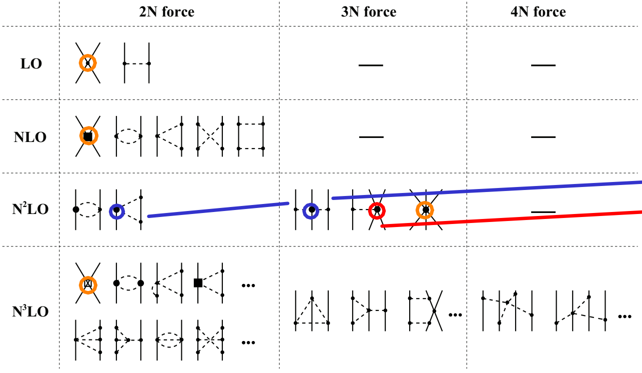


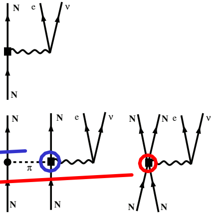
Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





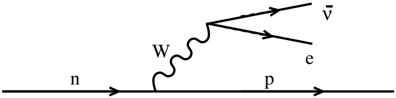
Weinberg, van Kolck, Kaplan, Savage, Epelbaum, Kaiser, Meißner...

Park, Gazit, Klos, Hoferichter...

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

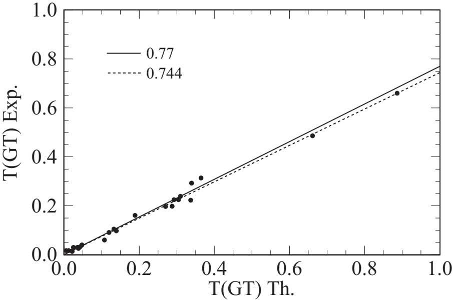
Gamow-Teller transitions: quenching

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



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

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



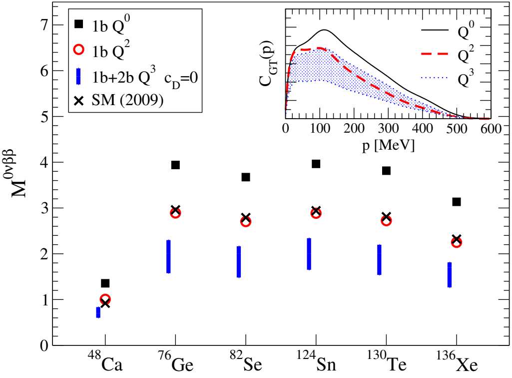
Martínez-Pinedo et al. PRC53 2602 (1996)

Theory needs to “quench“ Gamow-Teller operator to reproduce Gamow-Teller lifetimes: problem in nuclear many-body wf or operator?

This puzzle has been the target of many theoretical efforts:

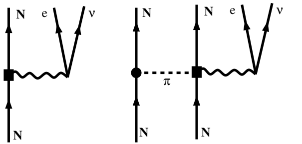
Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...

Nuclear matrix elements with 1b+2b currents

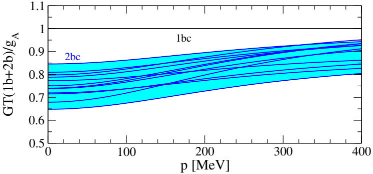


JM, Gazit, Schwenk PRL107 062501 (2011)

2b currents
reduce matrix elements
$\sim 20\% - 50\%$



Momentum transfer $p \sim m_\pi$,
reduces quenching ⇓

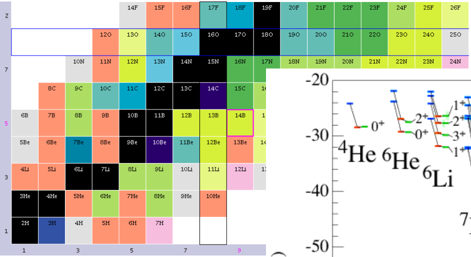


Smaller quenching $q = 0.96...0.92$

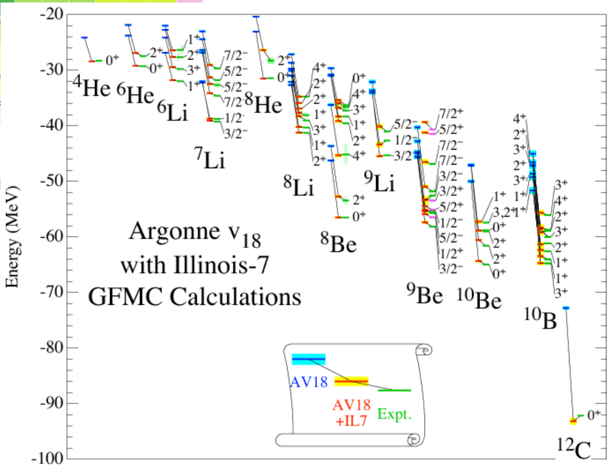
Ekström et al. PRL113 262504 (2014)

Improved (ab initio) calculations needed

Green’s function Monte Carlo



Green’s function Monte Carlo



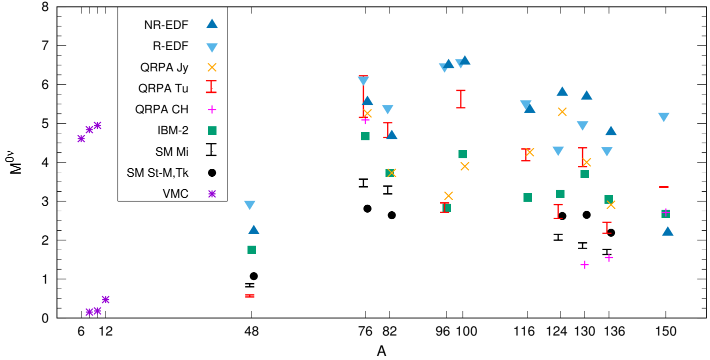
NN forces
do not reproduce
binding energies
and spectra:
need 3N forces

Good agreement
with 3N forces

$0\nu\beta\beta$ decay matrix elements in very light nuclei

Variational Monte Carlo (VMC) $0\nu\beta\beta$ decay matrix elements in $A \leq 12$

Pastore et al. arXiv:1710:05026



Larger/smaller matrix elements given by same/different nuclear isospin

VMC free from "quenching": reproduce β decay with $\boldsymbol{\sigma}\tau$ + 2b (small)

Anchor for other ab initio calculations that can extend to heavier nuclei

Outline

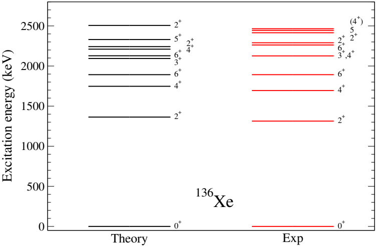
Present status of $0\nu\beta\beta$ decay nuclear matrix elements

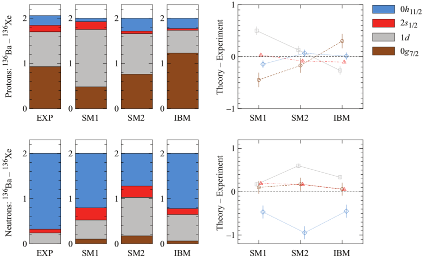
Future prospects for $0\nu\beta\beta$ nuclear matrix element calculations

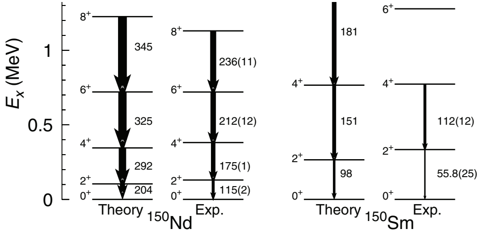
Can nuclear structure experiments help with $0\nu\beta\beta$ decay?

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)

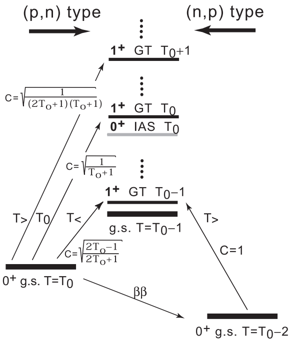
Rodríguez et al. PRL105 252503 (2010)

...

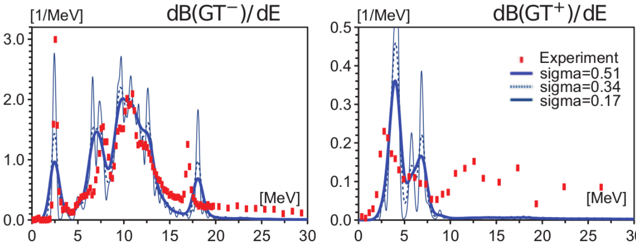
Vietze et al. PRD91 043520 (2015)

Gamow-Teller strength distributions

Gamow-Teller (GT) distributions well described by theory (quenched)



Freckers et al.
NPA916 219 (2013)



Iwata et al. JPSCP 6 03057 (2015)

$$\langle 1_f^+ | \sum_i [\boldsymbol{\sigma}_i \tau_i^\pm]^{\rm eff} | 0_{\rm gs}^+ \rangle , \quad [\boldsymbol{\sigma}_i \tau^\pm]^{\rm eff} \approx 0.7 \boldsymbol{\sigma}_i \tau^\pm$$

$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \boldsymbol{\sigma}_n \tau_n^- | 1_k^+ \rangle \langle 1_k^+ | \sum_m \boldsymbol{\sigma}_m \tau_m^- | 0_i^+ \rangle}{E_k - (M_i + M_f)/2}$$

Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance
in double charge-exchange reactions ^{48}Ca(pp,nn)^{48}Ti proposed in 80's

Auerbach, Muto, Vogel... 1980's, 90's

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

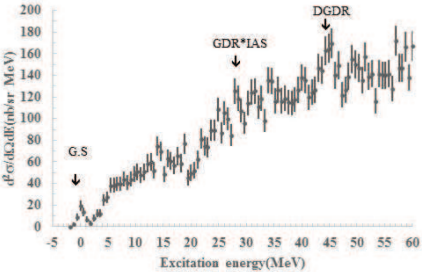
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

Capuzzello et al. EPJA 51 145 (2015), Takahisa, Ejiri et al. arXiv:1703.08264

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

Two-nucleon transfers related to
$0\nu\beta\beta$ decay matrix elements

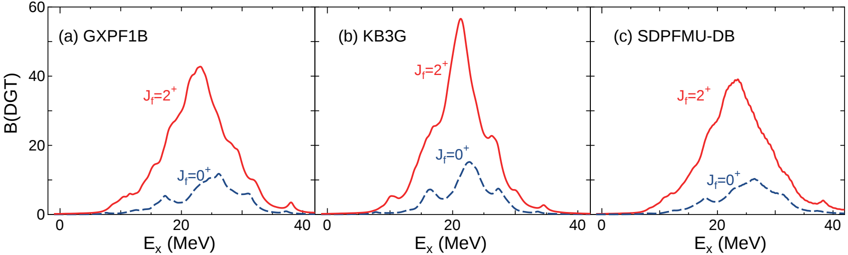
Brown et al. PRL113 262501 (2014)



^{48}Ca Double Gamow-Teller distribution

Calculate with shell model ^{48}Ca 0^+_{gs} Double Gamow-Teller distribution

$$B(DGT^-;\lambda;i\to f)=\frac{1}{2J_i+1}\left|\left\langle {}^{48}\mathrm{Ti}\left|\left|\left[\sum_i \boldsymbol{\sigma}_i\tau_i^- \times \sum_j \boldsymbol{\sigma}_j\tau_j^-\right]^{(\lambda)}\right|\right|{}^{48}\mathrm{Ca}_{gs}\right\rangle\right|^2$$



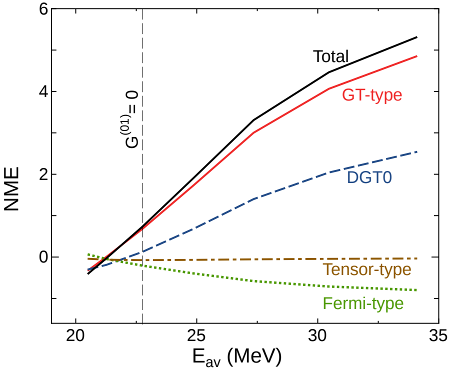
Shell model calculation with Lanczos strength function method

Double GT resonances in one and two shells rather similar result

Shimizu, JM, Yako, arXiv:1709.01088

^{48}Ca double GT resonance and $0\nu\beta\beta$ decay

Correlation between Double Gamow-Teller resonance in ^{48}Ca and $0\nu\beta\beta$ decay nuclear matrix element



Energy of DGT resonance with accuracy to $\sim$1MeV, can give insight on the value of $0\nu\beta\beta$ decay nuclear matrix element

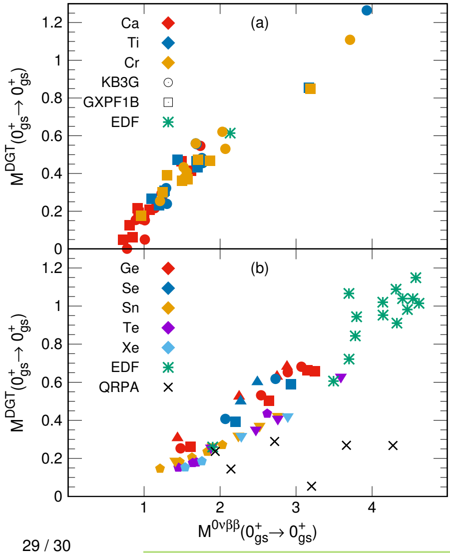
$$E_{\rm av} = \frac{\sum_f E_f B(DGT^-, i \to f)}{\sum_f B(DGT^-, i \to f)}$$

Might be feasible in near future

Shimizu, JM, Yako, arXiv:1709.01088

In progress: sensitivity to other nuclear structure correlations

Double Gamow-Teller and $0\nu\beta\beta$ decay



DGT transition to ground state

$M^{DGT} =$

$\langle F_{gs} || [\sum_i \boldsymbol{\sigma}_i \tau_i^- \times \sum_j \boldsymbol{\sigma}_j \tau_j^-]^0 || I_{gs} \rangle|^2$

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

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

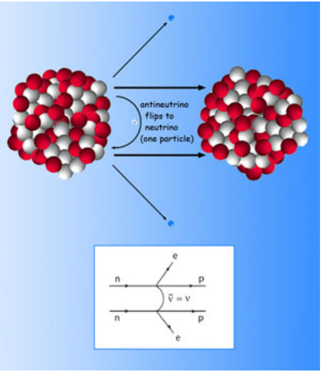
disagreement to QRPA

Shimizu, JM, Yako, arXiv:1709.01088

Summary

Reliable nuclear matrix elements needed to plan and fully exploit impressive experiments looking for neutrinoless double-beta decay

- Matrix element differences
  between present calculations, factor 2 – 3
- ^{48}Ca and ^{76}Ge matrix elements
  in large configuration space increase $\sim$ 30%,
  missing correlations introduced in IBM, EDF
- First ab initio calculations with 2b currents
  small matrix elements (due to light nuclei?)
  with no additional "quenching" needed,
  stay tuned for ab initio ^{48}Ca matrix elements
- Double Gamow-Teller transitions
  can give insight on $0\nu\beta\beta$ matrix elements



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