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

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"Recent developments in neutrino physics and astrophysics"
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東京大学
THE UNIVERSITY OF TOKYO

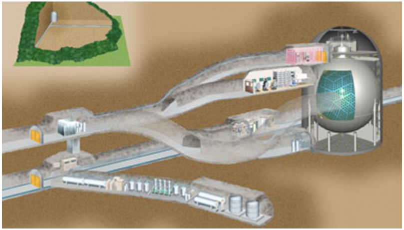
Nuclear physics and fundamental symmetries

Neutrinos, dark matter... can be studied in high-energy experiments

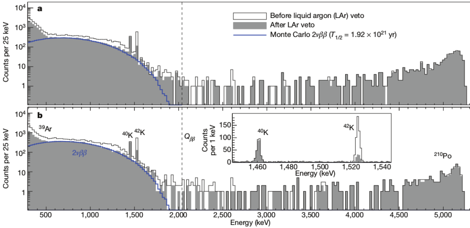
Nuclear physics offers an alternative:
Nuclei are abundant in huge numbers $N_A = 6.02\ 10^{23}$ nuclei in A grams!

Lots of material over long times provides access to detect
very rare decays and very small cross-sections!

Limit background: underground



KamLAND-Zen, GERDA...



Nuclear physics and neutrinoless $\beta\beta$ decay

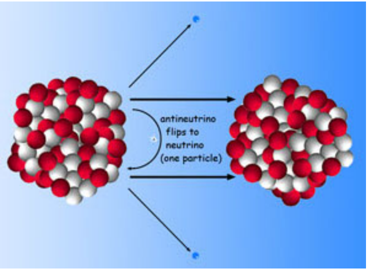
Neutrinos, dark matter studied in experiments using nuclei

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

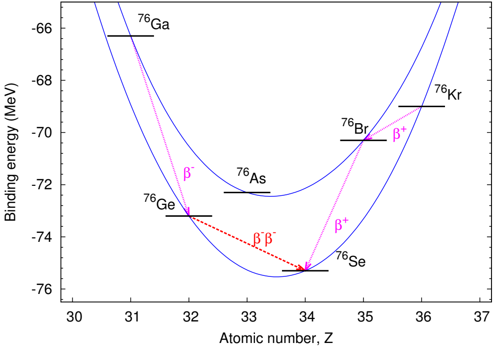
$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor

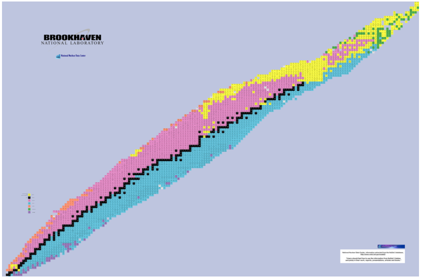


Neutrinoless double-beta decay

Lepton-number violation, Majorana nature of neutrinos

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



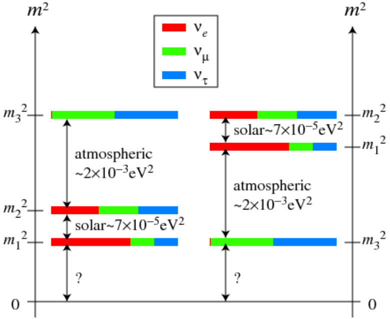


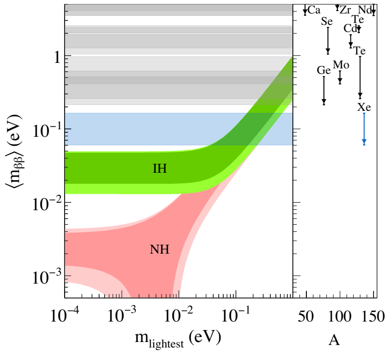
Best limit: ^{130}Te (CUORE), ^{76}Ge (GERDA), ^{136}Xe (EXO, KamLAND-Zen)

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, $m_{\beta\beta} = |\sum U_{ek}^2 m_k|$, and hierarchy





KamLAND-Zen, PRL117 082503(2016)

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

Outline

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

What can we learn from other nuclear experimental data?

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

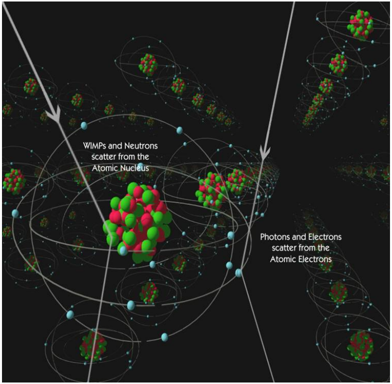
Calculating nuclear matrix elements

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...

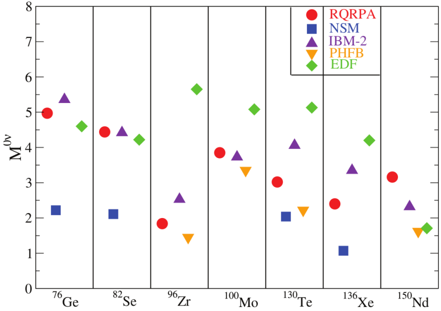
- Lepton-nucleus interaction:
  Study hadronic current in nucleus: phenomenological approaches, effective theory of QCD



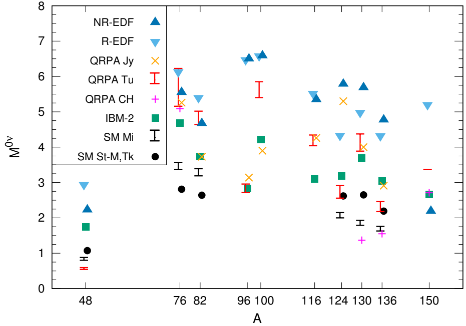
CDMS Collaboration

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

Comparison of nuclear matrix element calculations: 2012 vs 2017



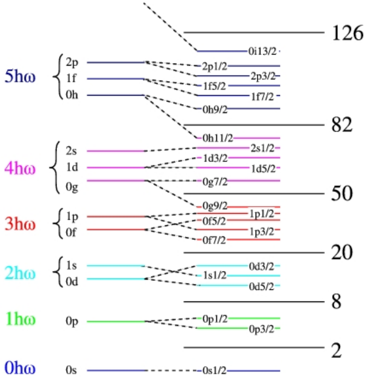
Vogel, J. Phys. G 39 124002 (2012)



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

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

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

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

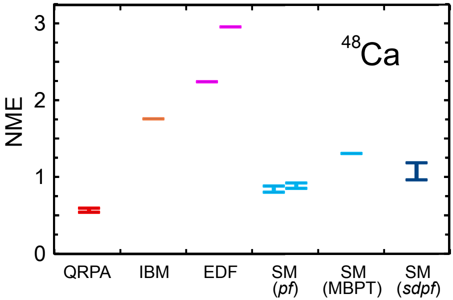
Dimension $\sim$

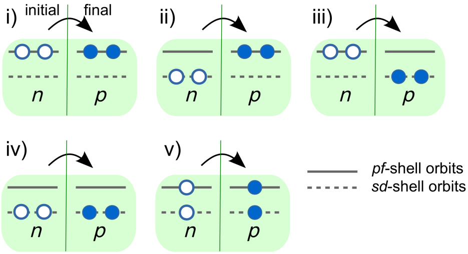
$$\binom{(p+1)(p+2)_{\nu}}{N}\binom{(p+1)(p+2)_{\pi}}{Z}$$

Shell model: enlarging configuration space

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)





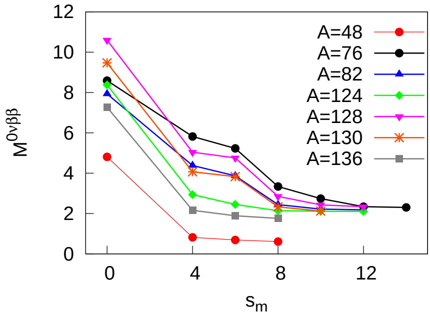
Contributions dominated by pairing
2 particle – 2 hole excitations
enhance the $\beta\beta$ matrix element,

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

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

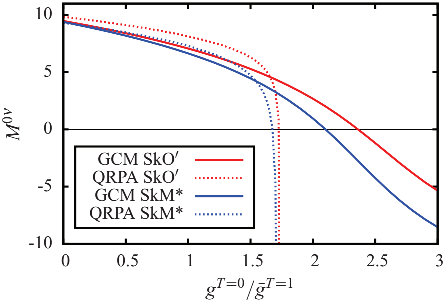
$0\nu\beta\beta$ decay favoured by proton-proton, neutron-neutron pairing, but it is disfavored by proton-neutron pairing

Ideal case: superfluid nuclei reduced with high-seniorities



Caurier et al. PRL100 052503 (2008)

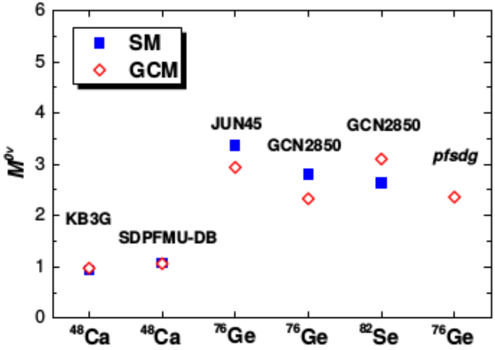
Addition of isoscalar pairing reduces matrix element value



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

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



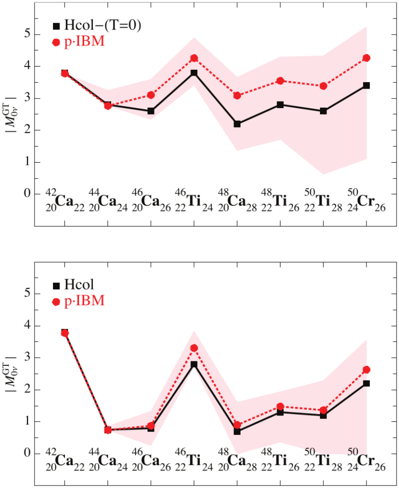
Jiao et al. arXiv:170703940

GCM approximates
shell model calculation

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

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

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

Outline

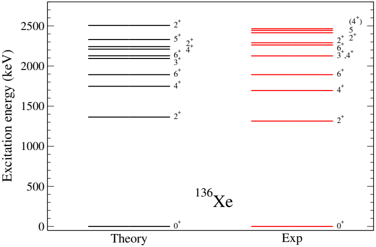
Present status of $0\nu\beta\beta$ decay nuclear matrix elements

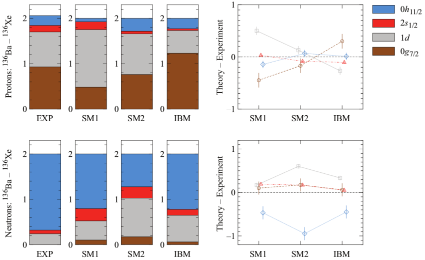
What can we learn from other nuclear experimental data?

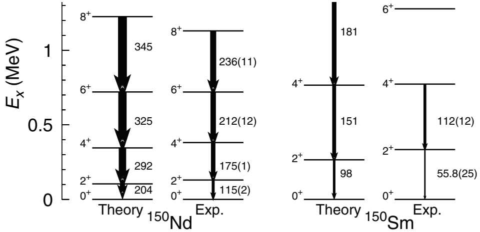
Future prospects for $0\nu\beta\beta$ nuclear matrix element calculations

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)

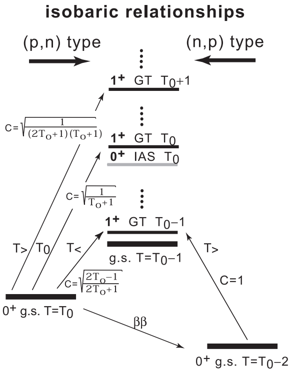
Rodríguez et al. PRL105 252503 (2010)

...

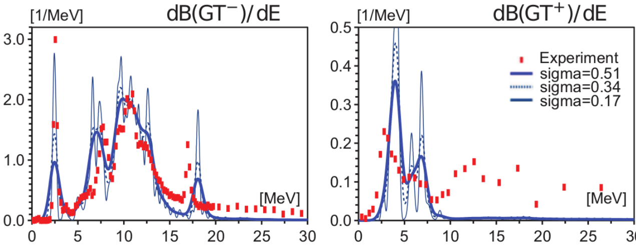
Vietze et al. PRD91 043520 (2015)

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)

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

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

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

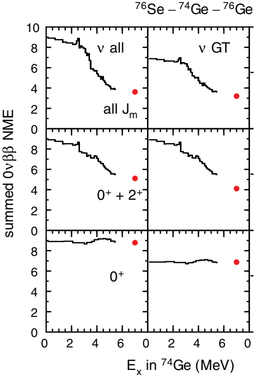
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

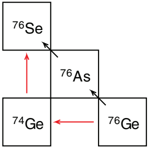
Capuzzello et al. EPJA 51 145 (2015)

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

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

Brown et al. PRL113 262501 (2014)





^{48}Ca Double Gamow-Teller distribution

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

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

Add/remove pairing

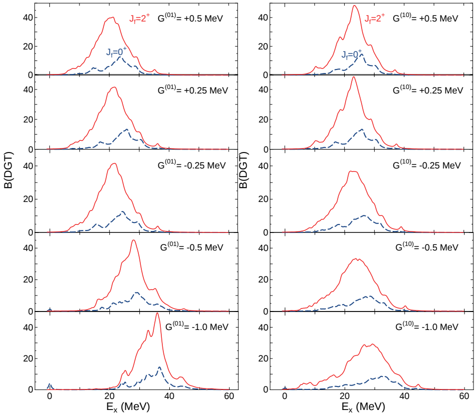
$$H' = H + G^{JT} P^{JT}$$

like-particle (T=1) or proton-neutron (T=0)

The properties of the DGT giant resonance very sensitive to pairing

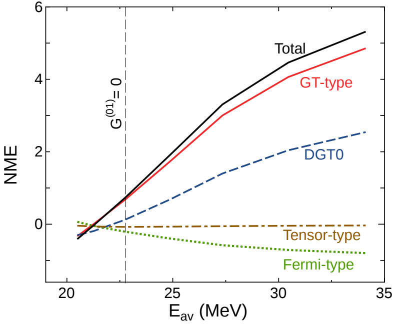
Similar to $0\nu\beta\beta$ decay!

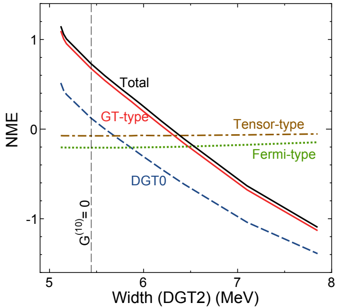
Shimizu, JM, Yako, arXiv:1709.01088



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

Correlation btw ^{48}Ca DGT resonance and $0\nu\beta\beta$ decay matrix element



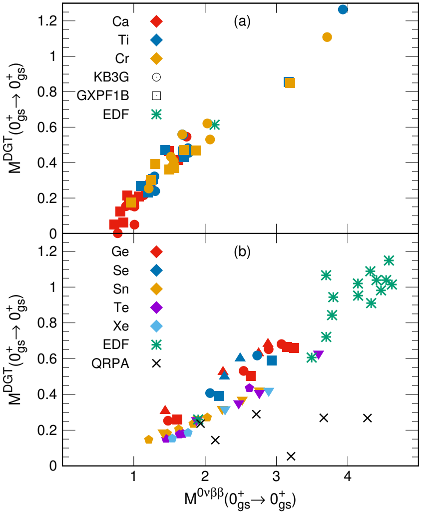


Energy of DGT resonance, to ∼1MeV, which may be feasible in the near future can give insight on the value of $0\nu\beta\beta$ decay matrix element

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

Shimizu, JM, Yako, arXiv:1709.01088

DGT to ground state and $0\nu\beta\beta$ decay



Shimizu, JM, Yako, arXiv:1709.01088

Very good linear correlation between DGT and $0\nu\beta\beta$ decay nuclear matrix elements

$$M^{\rm DGT} = \sqrt{B(DGT_-; 0; 0^+_{\rm gs} \to 0^+_{\rm gs})}$$

Correlation holds across wide range of nuclei, from Ca to Ge and Xe

Common to nuclear shell model and energy-density functional $0.5 \lesssim M^{0\nu\beta\beta} \lesssim 5$

Explained by dominance of short internucleon distances btw exchanged / decaying neutrons

Bogner et al. PRC86 064304 (2012)

Outline

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

What can we learn from other nuclear experimental data?

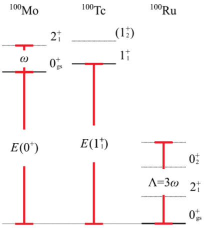
Future prospects for $0\nu\beta\beta$ nuclear matrix element calculations

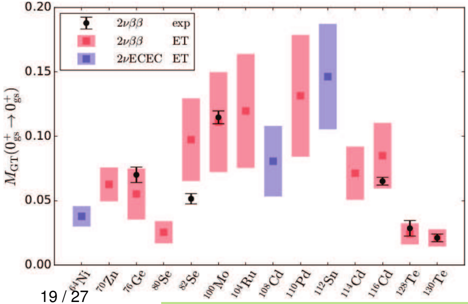
Nuclear matrix elements: theoretical uncertainty

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 breakdown scale
(systematic order by order expansion)





Use data on β decay
to predict $2\nu\beta\beta$ decay

Good agreement to data
with large error bars

$0\nu\beta\beta$ decay: no data to fit to...
use nuclear model instead

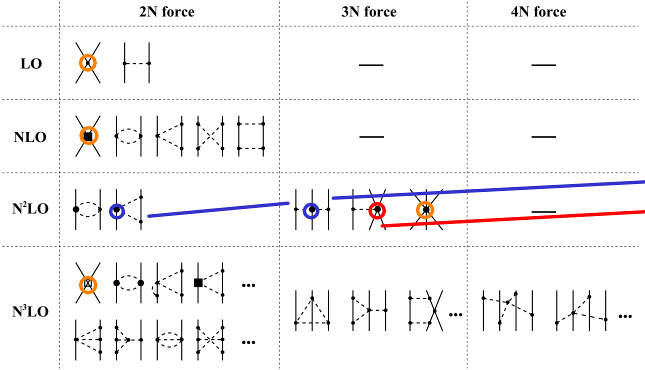
Coello-Pérez, JM, Schwenk,
arXiv:1708.06140

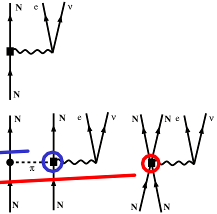
Chiral Effective Field Theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





Park, Gazit, Klos, Baroni...

Short-range couplings
fitted to experiment once

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

Ab initio many-body methods

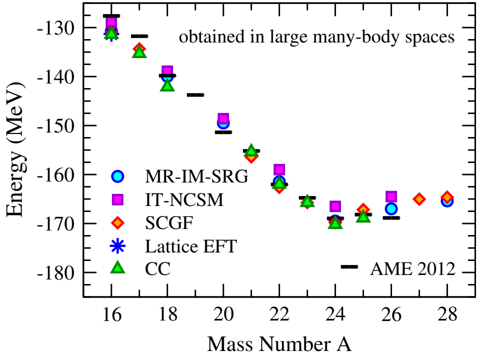
Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

No-core shell model
(Importance-truncated)

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

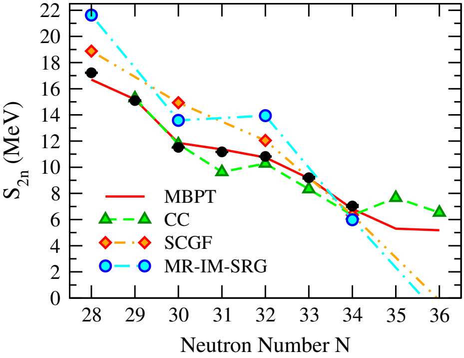
Self-consistent Green's function
Cipollone et al. PRL111 062501(2013)

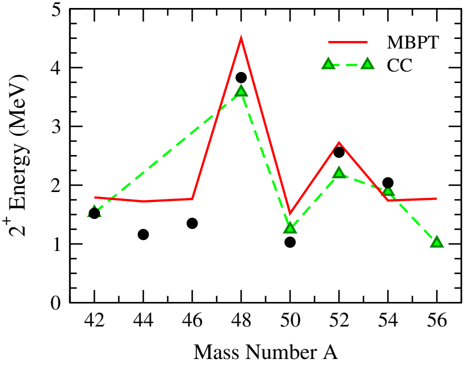
Coupled-clusters
Jansen et al. PRL113 142502(2014)



Calcium isotopes with NN+3N forces

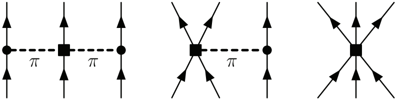
Calculations with NN+3N forces predict shell closures at ^{52}Ca, ^{54}Ca





$^{51-54}$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 nuclear force

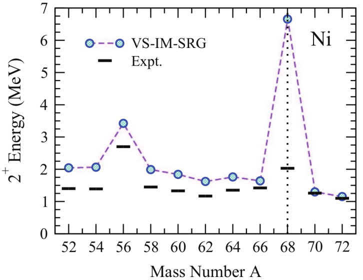
Success of ab initio methods
(unitary) transformation: $H' = U^\dagger H U$
Likewise for operators: $O' = U^\dagger O U$
First EM transition results published

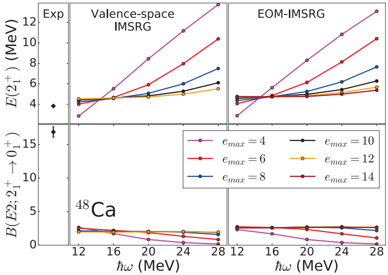
Ab initio single-β, $2\nu\beta\beta$ decay
calculations in light nuclei
give insight in "quenching" puzzle

^{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. arXiv 1705.05511



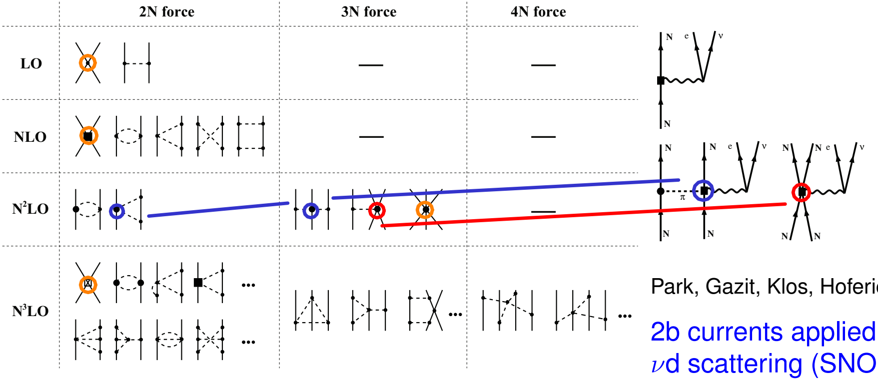


Chiral effective field theory

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

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents



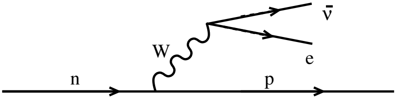
Park, Gazit, Klos, Hoferichter...

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

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

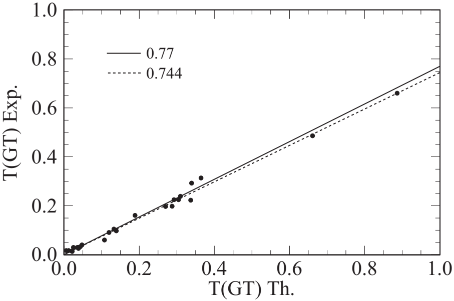
Gamow-Teller transitions: quenching

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



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

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



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:

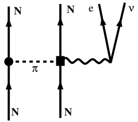
Arima, Rho, Towner, Bertsch and Hamamoto, Wildenthal and Brown...

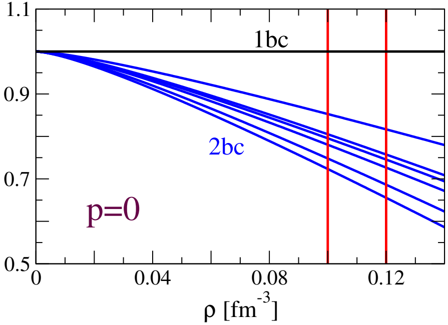
2b currents in medium-mass nuclei

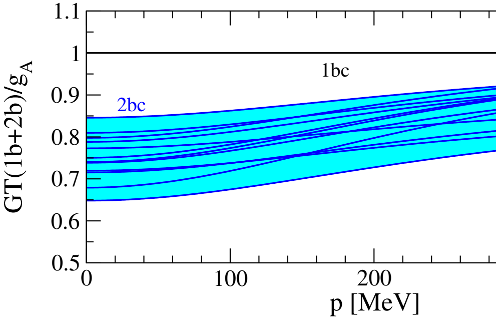
Normal-ordered 2b currents modify GT operator

JM, Gazit, Schwenk PRL107 062501 (2011)

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



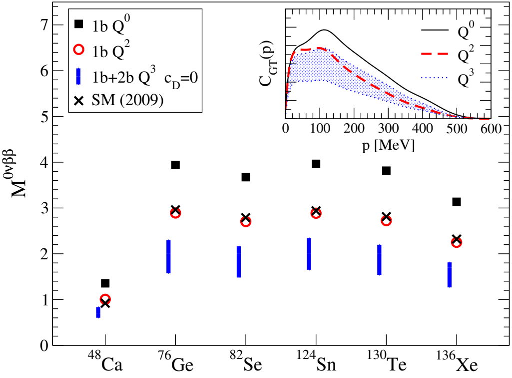




2b currents predict g_A quenching $q = 0.85 \ldots 0.66$

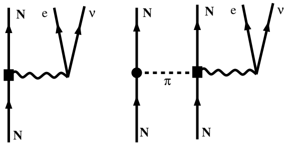
Quenching reduced at $p > 0$, relevant for $0\nu\beta\beta$ decay where $p \sim m_\pi$

Nuclear matrix elements with 1b+2b currents

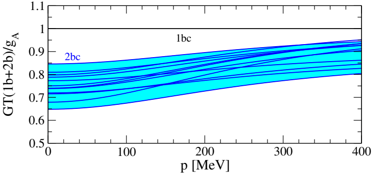


JM, Gazit, Schwenk PRL107 062501 (2011)

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



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



Smaller quenching $q = 0.96...0.92$

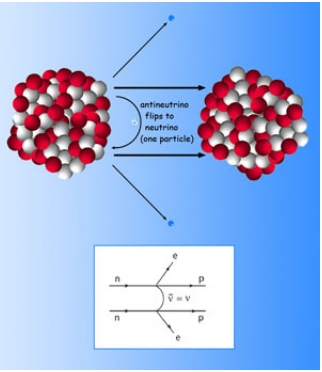
Ekström et al. PRL113 262504 (2014)

Improved (ab initio) calculations needed

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 $2 - 3$
- New ^{48}Ca and ^{76}Ge matrix elements in larger configuration spaces moderate $\sim 30\%$ increase or less
- Double Gamow-Teller transitions pursued in different labs very useful insight on value of $0\nu\beta\beta$ decay matrix elements
- Ab initio calculations on the way, consistent 2b currents (quenching?) evaluation of theoretical uncertainties



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