Which data and correlations can constrain $0\nu\beta\beta$ decay matrix elements?

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

"Neutrinoless Double-Beta Decay" INT program
Institute for Nuclear Theory, Seattle
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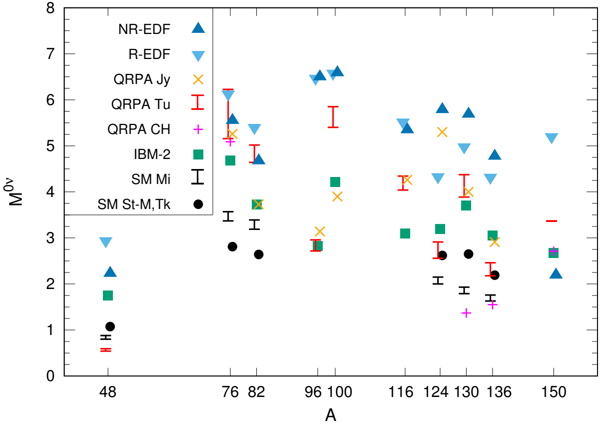
$0\nu\beta\beta$ decay nuclear matrix elements

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?

How can data/calculations help to constrain the matrix element values?

Outline

1. Data: Double Gamow-Teller transitions

2. Correlations: Light- and heavy-neutrino exchange mechanisms

3. Outlook

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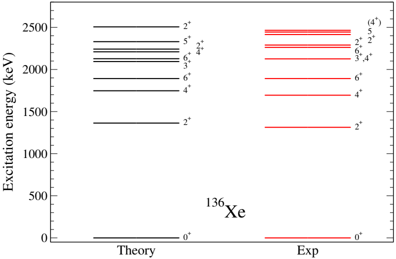
1. Data: Double Gamow-Teller transitions

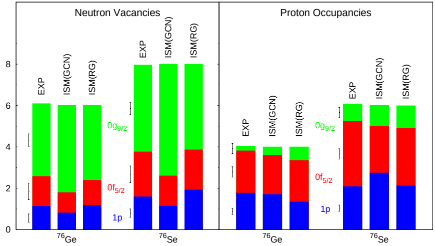
2. Correlations: Light- and heavy-neutrino exchange mechanisms

3. Outlook

Test of nuclear structure

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

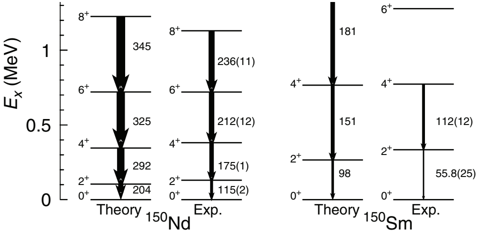




Shell model:

JM, Caurier, Nowacki, Poves

PRC80 048501 (2009)



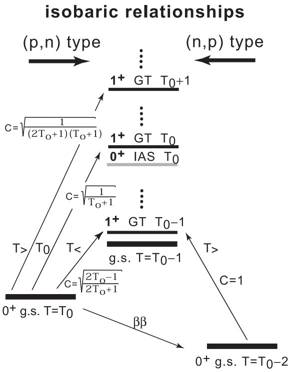
Energy-Density Functional:

Rodríguez, Martínez-Pinedo

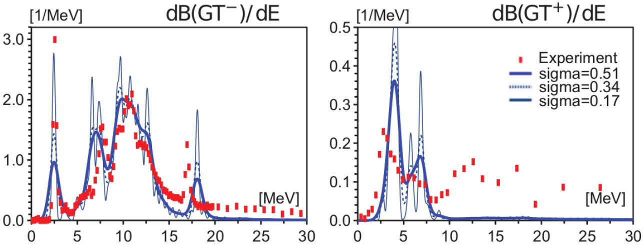
PRL105 252503 (2010)

Gamow-Teller strength distributions

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



Freckers et al.
NPA916 219 (2013)



Iwata et al. JPSCP 6 03057 (2015)

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

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

GT strengths combined related to $2\nu\beta\beta$ decay, but relative phase unknown

Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller resonance
in double charge-exchange reaction proposed decades ago

Auerbach et al. 1980’s, 90’s

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

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

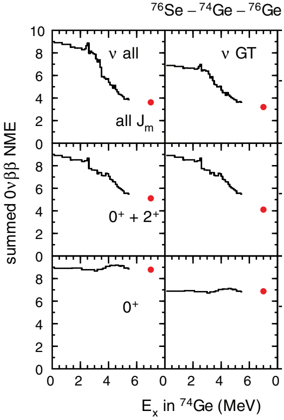
Capuzzello et al. EPJA 51 145 (2015)

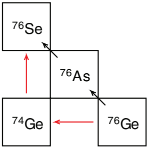
Additional test
of nuclear structure calculations

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)

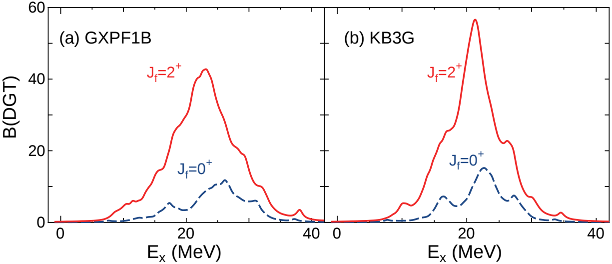




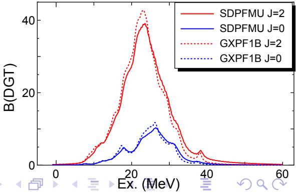
^{48}Ca Double Gamow-Teller distribution

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

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



Shimizu, JM, Yako
in preparation



Relatively independent of the shell model interaction

Effect of configuration space from *pf* to *sdpf* small

$\lambda=2$ dominates the double-GT resonance

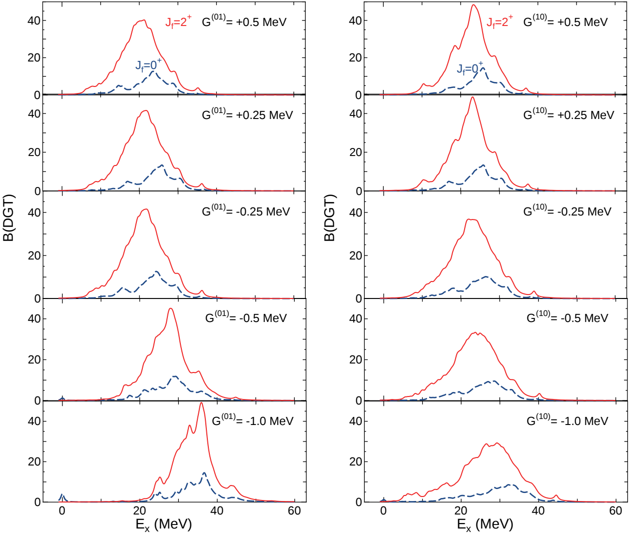
Double GT distribution: pairing

If double GT resonance related to $\beta\beta$ decay, depend on pairing correlations

Add pairing interaction to shell model H with varying strength G, attractive and repulsive

$$H' = H + G^{01} P^{J=0,T=1},$$

$$H'' = H + G^{10} P^{J=1,T=0}.$$

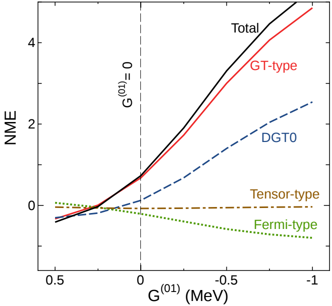


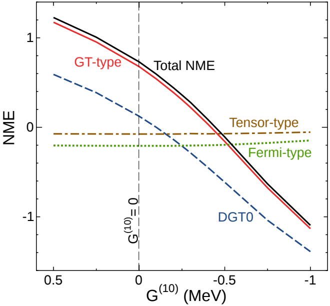
Isovector pairing Double GT resonance move to higher energy

Isoscalar pairing Double GT resonance increase width

$0\nu\beta\beta$ decay: pairing

$0\nu\beta\beta$ decay matrix element also sensitive to isovector and isoscalar pairing

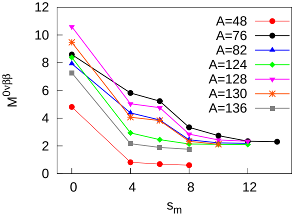




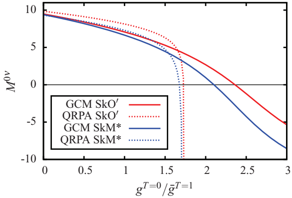
Pairing correlations enhance matrix element

Isoscalar pairing reduce matrix element

Agree with previous work



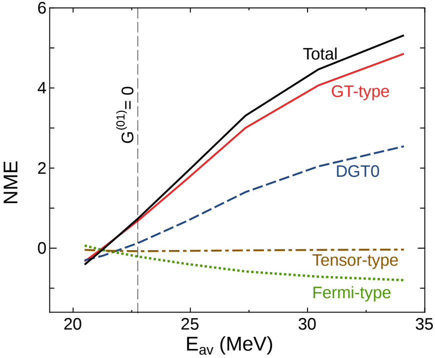
Caurier et al. PRL100 (2008)

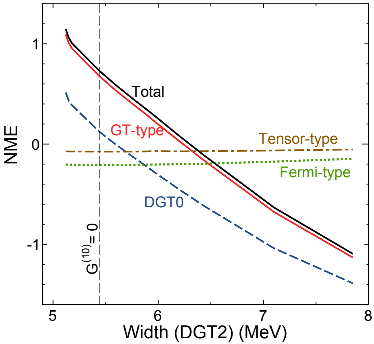


Hinohara, Engel PRC90 (2014)

Double GT resonance and $0\nu\beta\beta$ decay

Correlation between double GT resonance and $0\nu\beta\beta$ decay matrix element





Location of double GT resonance, to ∼1MeV, can constrain $0\nu\beta\beta$ decay matrix element

Double GT resonance width also useful more experimental precision needed

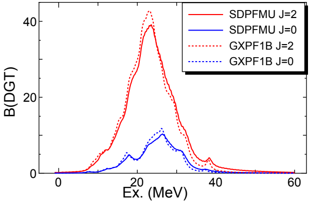
$$E_{\rm av} = \frac{\sum_f E_f B(DGT^-, i \rightarrow f)}{\sum_f B(DGT^-, i \rightarrow f)}$$

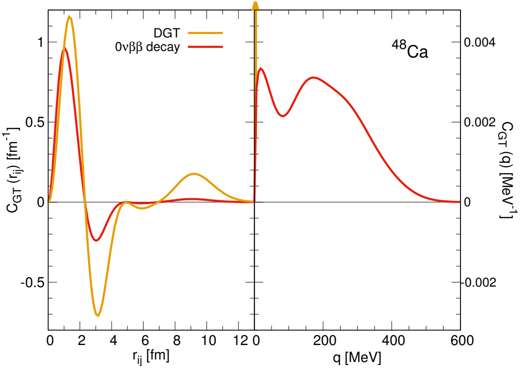
$$\sigma_{DGT} = \sqrt{\frac{\sum_f (E_f - E_{\rm av})^2 B(\mathrm{DGT}^-, i \rightarrow f)}{\sum_f B(\mathrm{DGT}^-, i \rightarrow f)}}$$

Double GT to ground state and $0\nu\beta\beta$ decay

Double GT transition to ground state of final nucleus closest similarity to $0\nu\beta\beta$ decay

Both matrix elements tiny sum rule fraction



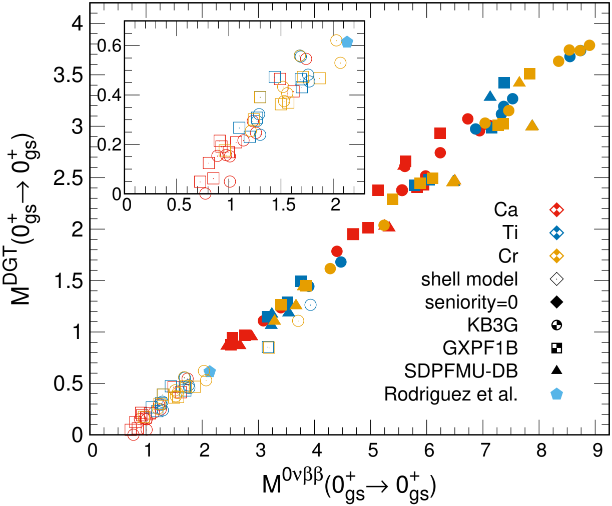


$0\nu\beta\beta$ decay matrix element limited to shorter range

Short-range part
also dominant
in double GT matrix element
cancellation
of long range parts

Shimizu, JM, Yako, in preparation

Double GT to ground state and $0\nu\beta\beta$ decay



Linear correlation
Double GT, $0\nu\beta\beta$ decay
matrix elements

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

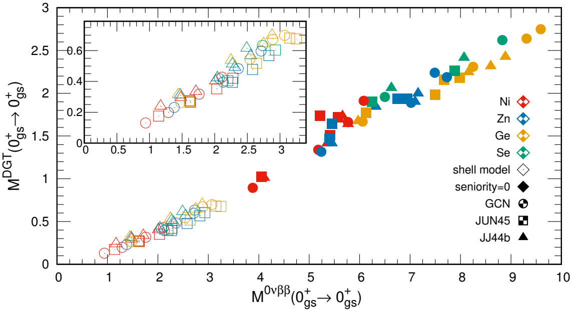
Correlation similar across
Ca, Ti, Cr nuclei

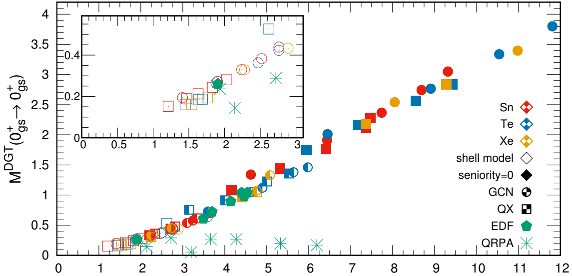
with and without
seniority correlations
$0.5 \lesssim M \lesssim 9$

for different
shell model interactions

in the *pf* shell
sdpf configuration space

Double GT to ground state and $0\nu\beta\beta$ decay





Linear correlation
Double GT, $0\nu\beta\beta$ decay
matrix elements

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

Correlation similar across nuclear chart

with and without seniority correlations
$0.5 \lesssim M \lesssim 12$

for different shell model interactions

agree with EDF
disagree with QRPA

Outline

1 Data: Double Gamow-Teller transitions

2 Correlations: Light- and heavy-neutrino exchange mechanisms

3 Outlook

$0\nu\beta\beta$ decay light- and heavy-neutrino exchange

Neutrinoless $\beta\beta$ decay mediated by light or heavy neutrinos

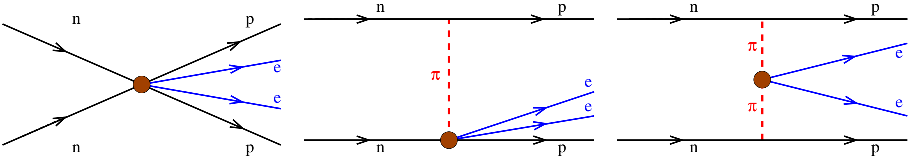
Barea, Horoi, Menéndez, Šimkovic, Suhonen...

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

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

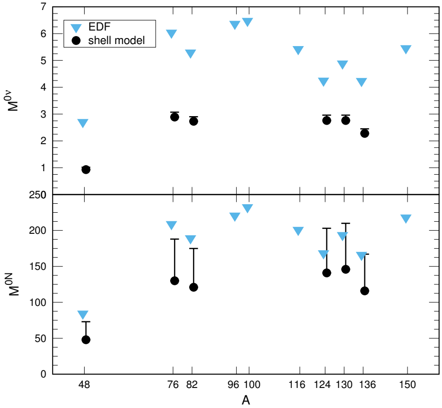
Same contributions in both channels

but in heavy-neutrino exchange the standard term becomes shorter range



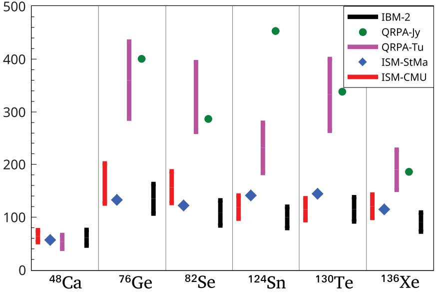
Comparing heavy-neutrino exchange matrix elements

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



JM to be submitted

Song et al. PRC95 024305 (2017)



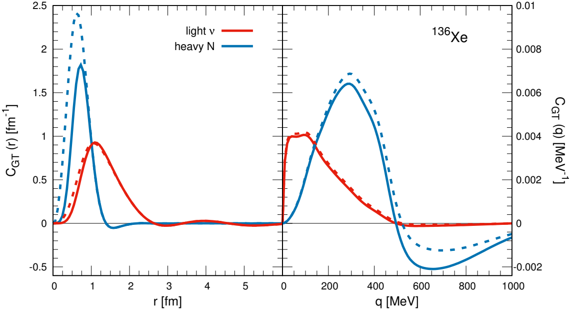
Neacsu et al. PRC100 052503 (2015)

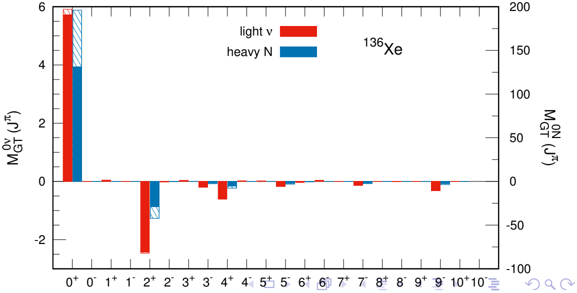
Heavy-neutrino matrix element

Compared to
light-neutrino exchange

heavy neutrino exchange
dominated by shorter range,
larger momentum transfers

heavy neutrino exchange
contribution
from $J > 0$ pairs smaller

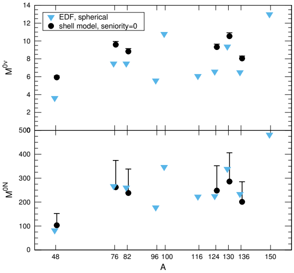




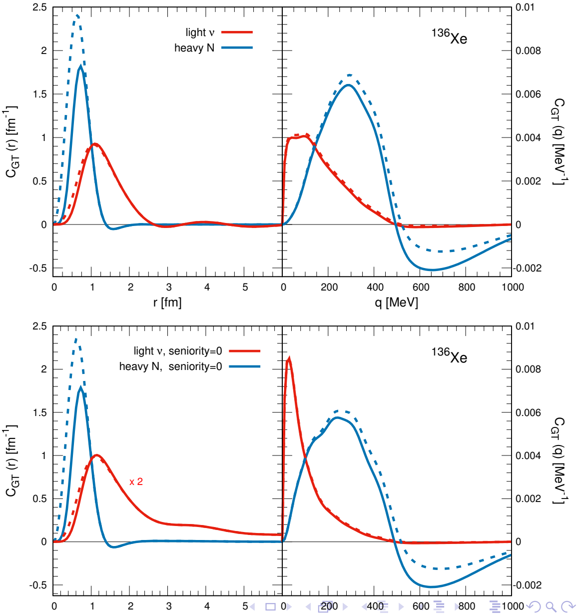
Uncorrelated heavy-neutrino matrix element

Uncorrelated (seniority-zero) light- and heavy-neutrino matrix elements agree for shell model and EDF

JM, Rodríguez et al. PRC90 (2014)



Correlations (high-seniority) affect long-range part small momentum transfers only relevant for light-neutrino exchange

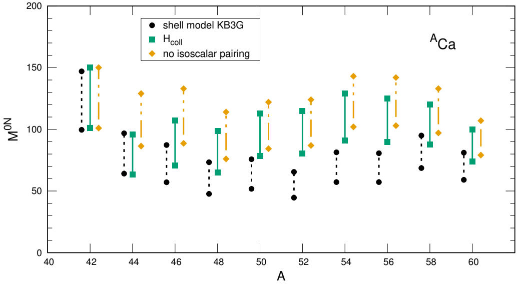


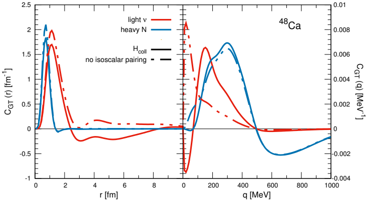
Differences due to isoscalar pairing?

Separable shell model collective interaction Dufour, Zuker PRC54 1653(1996)

$$H_{\rm coll} = H_M + g^{T=1} \sum_{n=-1}^{1} S_n^\dagger S_n + g^{T=0} \sum_{m=-1}^{1} P_m^\dagger P_m + g_{ph} \sum_{m,n=-1}^{1} :\mathcal{F}_{mn}^\dagger \mathcal{F}_{mn}: + \chi \sum_{\mu=-2}^{2} :Q_\mu^\dagger Q_\mu:$$

Find long-range piece which does not affect heavy-neutrino exchange: isoscalar pairing Vogel, Zirnbauer, Engel, Hinohara, JM...





Suggest difference between shell model, EDF isoscalar pairing

Same reason for disagreement shell model and IBM?

Outline

1. Data: Double Gamow-Teller transitions

2. Correlations: Light- and heavy-neutrino exchange mechanisms

3. Outlook

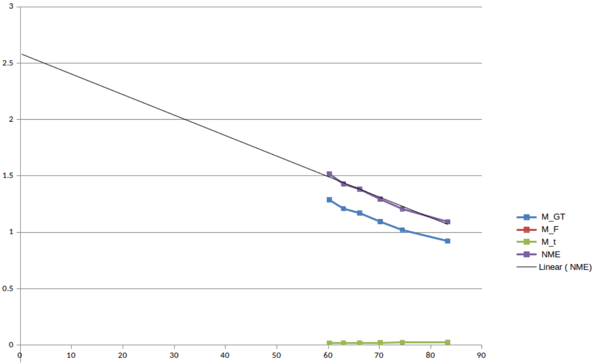
Monte Carlo shell model: ^{76}Ge matrix element

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. PRL117 172502 (2016)



Matrix element
as a function of $\langle \Delta H^2 \rangle$

Convergence very slow
with respect to basis state #

Pairing correlations
probably not fully captured
in non-converged
calculations

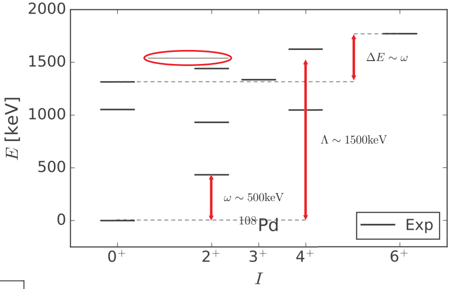
Basis on seniority scheme?

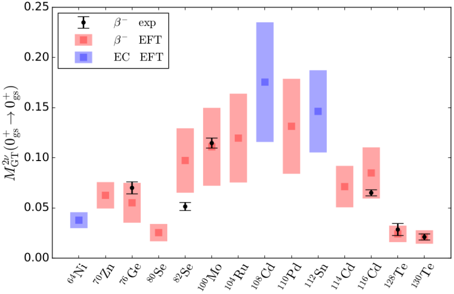
Tsunoda, Shimizu, et al. in prog.

Effective field theory for β and $\beta\beta$ 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, JM, Schwenk, in progress

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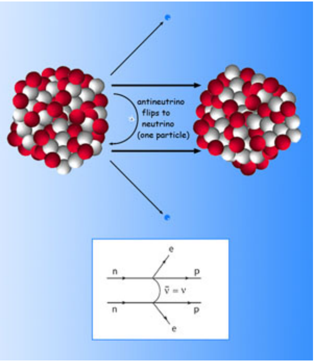
February 26 - March 30, 2018
C. Barbieri, O. Benhar, A. Galindo-Uribarri, A. Lovato, J. Menéndez

Summary

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

- Double Gamow-Teller resonances
  test of nuclear structure calculations
  correlation to $0\nu\beta\beta$ decay matrix elements
- Double Gamow-Teller transition
  to ground state of final nucleus
  linear correlation to $0\nu\beta\beta$ decay matrix element
  across the nuclear chart (shell model)
- Shell model & EDF
  agreement for heavy-neutrino exchange
  and uncorrelated matrix elements
  suggest difference due to isoscalar pairing
- Shell model Monte Carlo for ^{76}Ge underway



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