Neutrinoless double-beta decay from an effective field theory for heavy nuclei

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European Research Council
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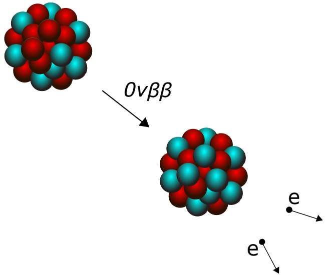
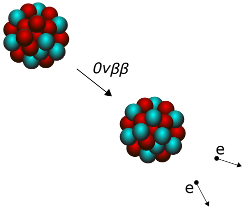


Wednesday 18th January, 2023

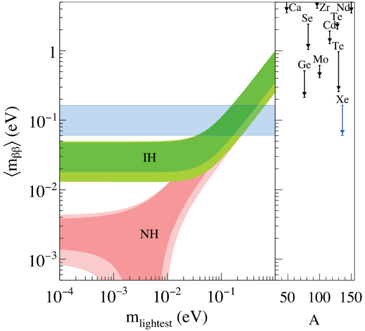


- lepton-number violation: no -emission
  - ! insights to matter and anti-matter asymmetry
- : neutral and massive
  - ! Majorana (= ‾) or Dirac (≠ ‾) particles?
- Standard Model: lepton-number conservation
  - ! BSM physics

open questions

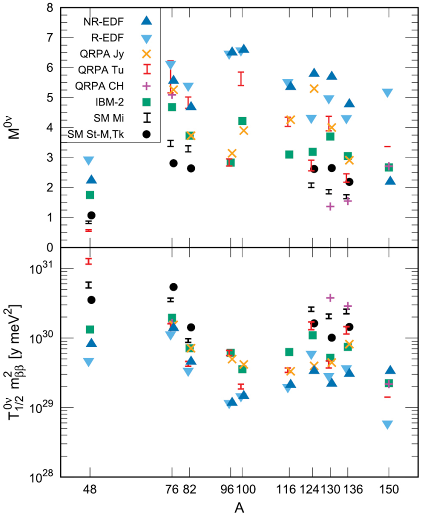
- mechanism(s) governing 0 decay
- mass hierarchy of neutrinos

answering these questions can be hindered by uncertainty of NMEs



Engel and Menéndez,
Rep. Prog. Phys. 80, 046301 (2017)

Motivation: experimental side



Engel and Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

- phenomenological calculations for medium-mass or heavy nuclei
- top:
  deviation up to factor of three
- bottom - translation:
  up to an order of magnitude in half-life
- experiment:
  half-life   required material

large NME uncertainty:

- severe consequences for planning experiments
- current uncertainty estimation:
  variation of model parameters

reliable uncertainty quantification → EFT for medium-mass and heavy nuclei

Effective Field Theory for heavy nuclei

Coello Pérez and Papenbrock Phys. Rev. C 92, 014323 (2015),
Coello Pérez and Papenbrock Phys. Rev. C 92, 064309 (2015),
Coello Pérez, Menéndez and Schwenk, Phys. Rev. C 98, 045501 (2018)

- phonon (quadrupole excitation) and fermion (neutron or proton) degrees of freedom

$$[d\;, d^\dagger] = \quad ; \quad \{n\;, n^\dagger\} = \quad ; \quad \{p\;, p^\dagger\} =$$

- reference state: ground state (gs) of spherical even-even core $|0\rangle$
- nucleus: reference state coupled to fermions and/or phonons

$$|J_f M_f; j_p; j_n\rangle = \left(n^\dagger \quad p^\dagger\right)^{(J_f)} |0\rangle\,; \qquad \text{gs of odd-odd nucleus}$$

Effective Field Theory for heavy nuclei

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- phonon (quadrupole excitation) and fermion (neutron or proton) degrees of freedom

$$[d\ ;d^y] = \quad ; \quad fn\ ;n^y g = \quad ; \quad fp\ ;p^y g =$$

- reference state: ground state (gs) of spherical even-even core $j0i$
- nucleus: reference state coupled to fermions and/or phonons

$$jJ_f M_f ; j_p ; j_n i = \left(n^y \quad p^y\right)^{(J_f)} j0i\ ; \qquad \text{gs of odd-odd nucleus}$$

- power counting: $Q^n = \left(\frac{!}{\ }\right)^n$, n =number of phonons
  breakdown scale at three-phonon level: $= 3! \quad 2 \quad 3$ MeV
  $!$ quantification of theoretical uncertainties

- low-energy constants (LECs):
  quenching, high-energy physics & microscopic information
  $!$ fit to experimental data required

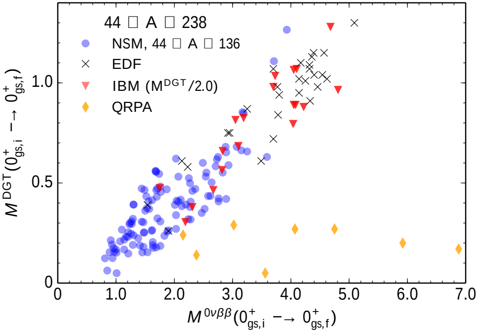
0 not observed - how to fit low-energy constants?

- LECs: experimental data of GT transitions available
- correlation between DGT and 0 NMEs
  Shimizu *et al.*, Phys. Rev. Lett. 120 14, 142502 (2018),

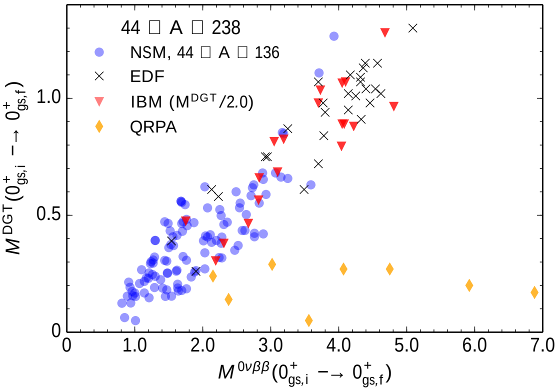
strategy:

1. DGT NMEs within EFT
2. correlation + DGT NMEs

! EFT 0 NME prediction with systematic quantified uncertainties

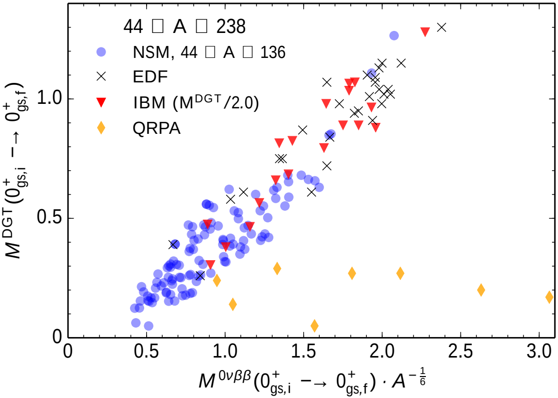


but first: correlation



- NSM, IBM and EDF results correlate very well
- QRPA results do not (see Javier's talk)

correlation		correlation coefficient r				
DGT	0	NSM	EDF	IBM	QRPA	NSM, EDF, IBM
		0:83	0:91	0:88	0:03	0:93
R[fm]		0:64	0:85	0:66	0:04	0:86
	$A^{\frac{1}{6}}$	0:90	0:93	0:93	0:03	0:95



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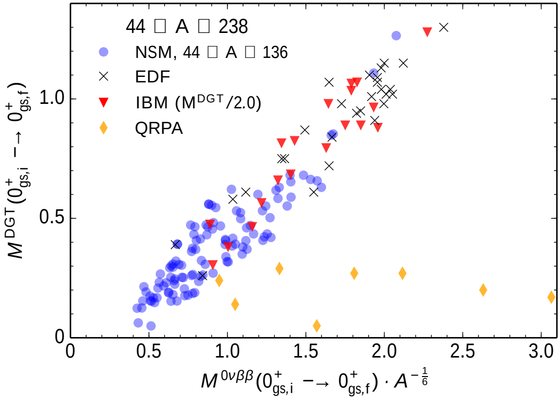

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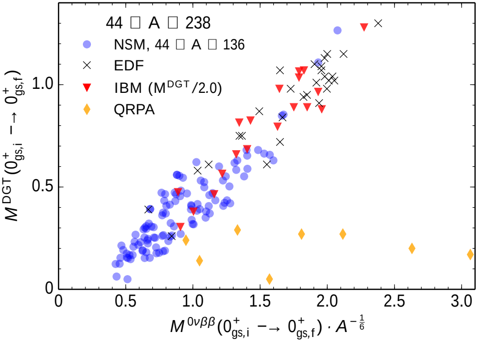
Correlation - motivation of factor



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$M^0_{NSM=IBM}$ implicit dependence on

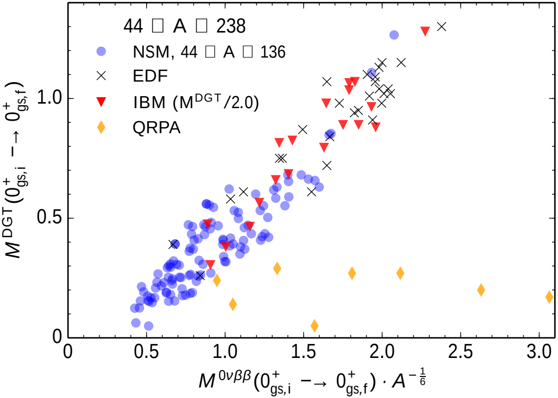
- harmonic oscillator length b $A^{1=6}$
- inverse radius $1=R$ with R $A^{1=3}$

best fit accounts for implicit dependence ! $b=R$ $A^{1=6}$

Correlation - linear fit of band

- application of correlation ! band
- fit of three linear functions to NSM data:

$$m \left(M^{0} \quad A^{1=6} \right) + n = M^{DGT}$$



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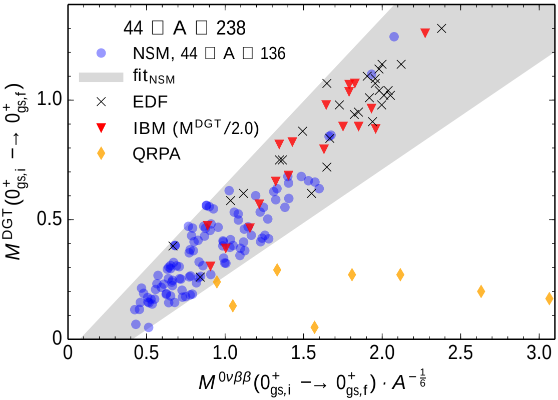

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- EDF and IBM enclosed by fit_{NSM}
- impressive mass range across nuclear chart (close to valley of stability)

Double Gamow-Teller transitions within EFT

- effective double GT operator between even-even states

$$\hat{O}_{DGT} = \left(\hat{O}_{GT} \quad \hat{O}_{GT}\right)^{(0)} = \underbrace{\overline{C}^2 \left((p^\dagger \quad \tilde{n})^{(1)} \quad (p^\dagger \quad \tilde{n})^{(1)} \right)^{(0)}}_{LO} + \cdots$$

- define spherical-tensor annihilation operator: $\tilde{a} = (-1)^{j_a+} \; a$
- higher-order terms not considered $\rightarrow$ uncertainty

$$\sum_{n=1}^{\infty} \left(\frac{\omega}{\;} \right)^n = 0.5$$

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- multifermion excitation of reference state

$$|0^+_{gs}\rangle = \frac{1}{2}\left(\left(n^\dagger \quad n^\dagger\right)^{(0)} \quad \left(p^\dagger \quad p^\dagger\right)^{(0)}\right)^{(0)} |0\rangle$$

Double Gamow-Teller transitions within EFT

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- final even-even nucleus $\rightarrow$ reference state $|0\rangle$

LO nuclear matrix element

$$M_{\mathrm{EFT}}^{\mathrm{DGT}} = \sqrt{\frac{4}{3(2j_n+1)(2j_p+1)}}\,\overline{C}^2$$

LO nuclear matrix element - Low-energy constant

$$M_{\mathrm{EFT}}^{\mathrm{DGT}} = \sqrt{\frac{4}{3(2j_n+1)(2j_p+1)}}\,\overline{C}^2$$

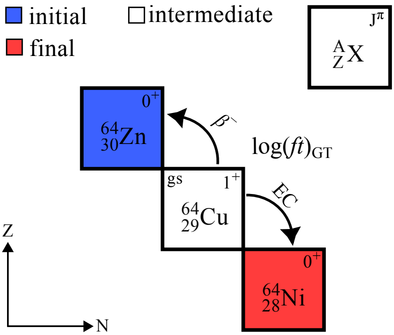
$\overline{C}^2$ fit to GT data: $C^2 = C_1 C_2$

Coello Pérez, Menéndez, and Schwenk, Phys. Lett. B 797, 134885 (2019)

- GT transition selection rule:

  $4J_{\mathrm{GT}} = 1 \quad 4\ {}_{\mathrm{GT}} = +$

- log(ft)-values of GT decays
- GT strengths from charge-exchange reactions



https://www.nndc.bnl.gov/ensdf/ ,
Grewe *et al.*, Phys. Rev. C 76, 054307 (2007), Thies *et al.*, Phys. Rev. C 86, 014304 (2012)
Frekers *et al.*, Phys. Rev. C 94, 014614 (2016), Thies *et al.*, Phys. Rev. C 86, 054323 (2012)
Puppe *et al.*, Phys. Rev. C 86, 044603 (2012), Puppe *et al.*, Phys. Rev. C 84, 051305 (2011)
Guess *et al.*, Phys. Rev. C 83, 064318 (2011)

LO nuclear matrix element - Low-energy constant

$$M^{DGT}_{EFT} = \sqrt{\frac{4}{3(2j_n + 1)(2j_p + 1)}}\,\overline{C}^2$$

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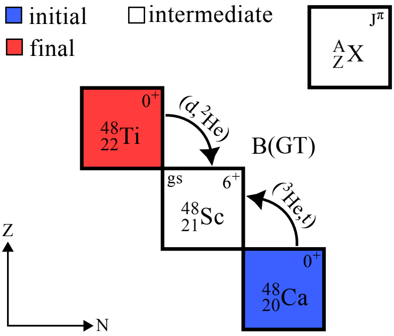

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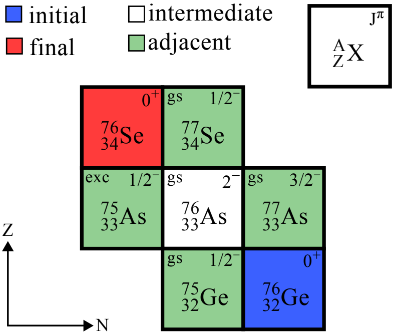
Nucleon orbitals

$$M_{\rm EFT}^{\rm DGT} = \sqrt{\frac{4}{3(2j_n+1)(2j_p+1)}}\,\overline{C}^2$$

- idea: nucleon orbitals from adjacent odd-mass nuclei
- dominant orbitals:
  ground or low-lying single-particle excited states

- $j_{\rm n} = \frac{1}{2}$
- $j_{\rm p} = \frac{3}{2}$ or $j_{\rm p} = \frac{1}{2}$



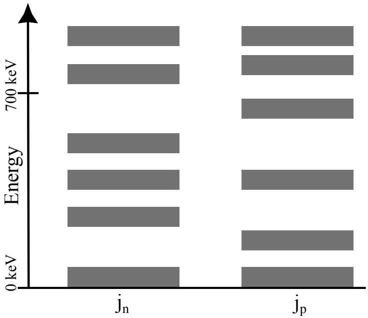
CB, Menéndez, Coello Pérez and Schwenk
PRC 106 (2022) 3, 034309

Nucleon orbitals

conditions:

- physically motivated thresholds
  - E 6 700 keV (dominance)
  - $T_{1=2}$ > 0:1 ns (single particle)
- GT transition selection rules
  - jj_n $j_p j$ 6 1 6 $jj_n + j_p j$
  - $_n$ $_p$ = +
- additional restrictions from
  - NSM: collective/not dominant

spectra of adjacent odd-mass nuclei



experimental data of odd-mass adjacent nuclei, https://www.nndc.bnl.gov/ensdf/

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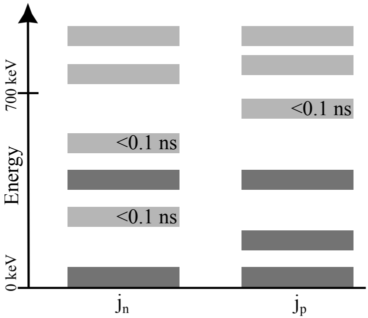

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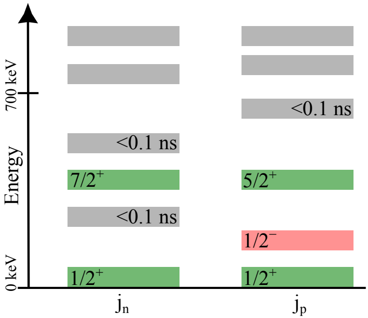

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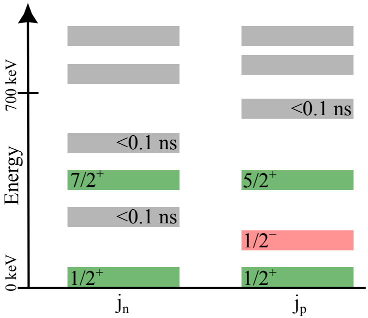

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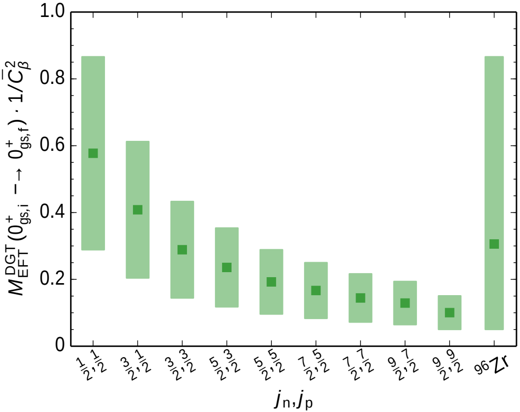
Nucleon orbitals contributions



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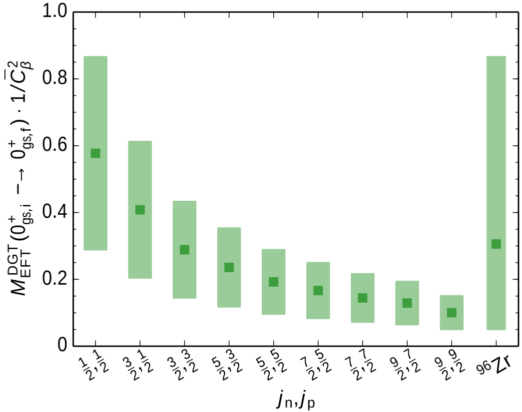
- truncation uncertainty: 50%
- ^{96}Zr central value: average of EFT DGT NME central values
- ^{96}Zr uncertainty: complete uncertainty range



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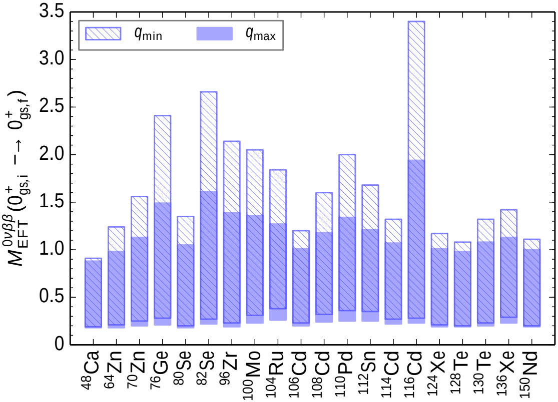
DGT NME + correlation band ! 0 NME



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- include quenching uncertainty from NSM GT transition
- $A > 48$: $q_{min} = 0{:}42$ and $q_{max} = 0{:}65$
- $A = 48$: $q_{min} = 0{:}70$ and $q_{max} = 0{:}80$
- range: $0{:}18 \; 6 \; M^{0}_{EFT} \; 6 \; 3{:}40$

Predictions in comparison

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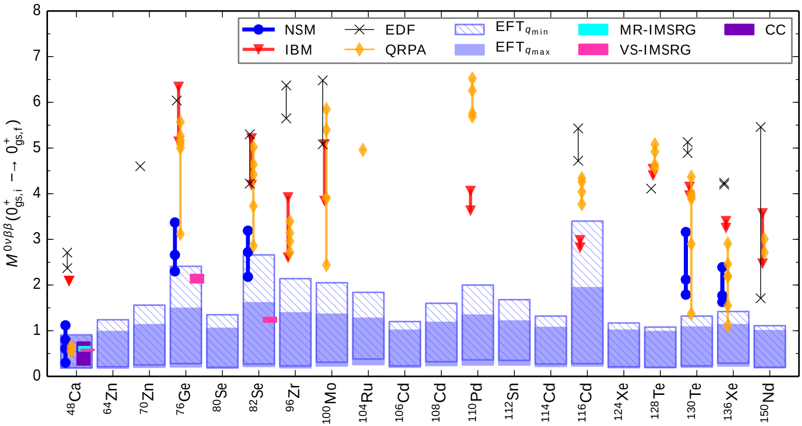
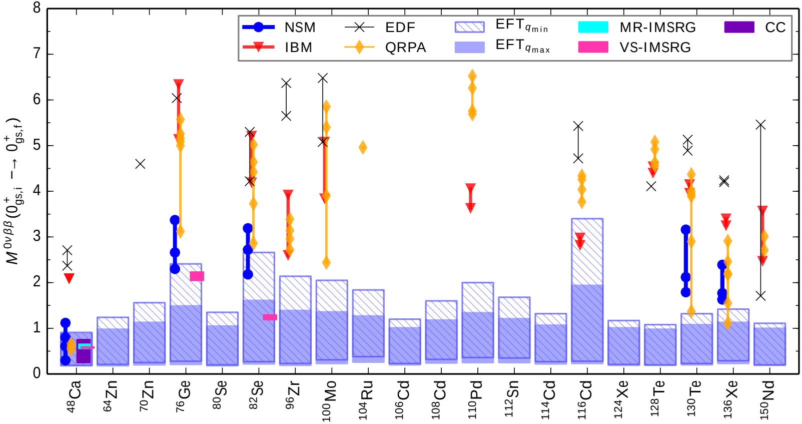


Menéndez *et al.*, **Nucl. Phys. A 818, 139 (2009), Horoi** *et al.*, **Phys. Rev. C 101, 044315 (2020), Iwata** *et al.*, **Phys. Rev. Lett. 116, 112502 (2016), Rodríguez** *et al.*, **Phys. Rev. Lett. 105, 252503 (2010), Song** *et al.*, **Phys. Rev. C 95, 024305 (2017), Šimkovic** *et al.*, **Phys. Rev. C 87, 045501 (2013), Fang** *et al.*, **Phys. Rev. C 97, 045503 (2018), Hyvärinen and Suhonen, Phys. Rev. C 91, 024613 (2015), Mustonen and Engel, Phys. Rev. C 87, 064302 (2013), Šimkovic** *et al.*, **Phys. Rev. C 98, 064325 (2018), Barea** *et al.*, **Phys. Rev. C 91, 034304 (2015), Yao** *et al.*, **Phys. Rev. Lett. 124, 232501 (2020), Belley** *et al.*, **Phys. Rev. Lett. 126, 042502 (2021), Novario** *et al.*, **Phys. Rev. Lett. 126, 182502 (2021)**



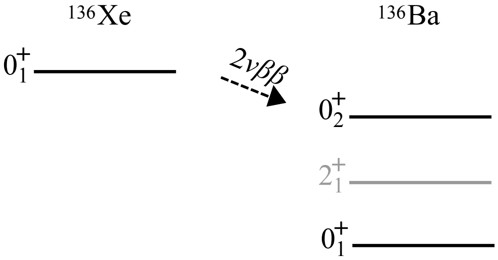
- range: $M^0_{\rm EFT}$ 6 3:40 vs. $M^0_{\rm other}$ 6 6:5 ! EFT smaller predictions
- (almost) overlap: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd and ^{136}Xe
- combined unc. from other models larger than EFT unc.
- consistent with *ab initio* predictions (MR-/VS-IMSRG & CC)

$$^{136}\mathrm{Xe}(0^+_{\mathrm{gs}}) \xrightarrow{2\nu\beta\beta} {}^{136}\mathrm{Ba}(0^+_2)$$

Jokiniemi, Romeo, CB, Kotila, Soriano, Schwenk and Menéndez

arXiv:2211.03764 in press at PLB

Motivation - ^{136}Xe(gs; 0_1^+) $\xrightarrow{2\nu\beta\beta}$ ^{136}Ba(exc; 0_2^+)



- test of predictions from different nuclear many body calculations
- useful, because applying these same methods for 0
- ongoing search for this decay at KamLAND-Zen and nEXO
  K. Asakura, et al., Nucl. Phys. A 946 (2016) 171,
  G. Adhikari, et al, J. Phys. G: Nucl. Part. Phys. 49 015104 (2022)

- fit LECs to data from decay or from charge-exchange reaction (GT-strength)
  ! predict 2 decay from gs to gs $M^2_{\mathrm{EFT}}(0^+_{\mathrm{gs}}\ !\ 0^+_{\mathrm{gs}})$ with single state dominance (SSD) approximation

$$M^2_{\mathrm{GT}} \quad hf\,jj\hat{O}_{\mathrm{GT}}jj1^+_1\,ih1^+_1\,jj\hat{O}_{\mathrm{GT}}jji\,i$$

- uncertainty associated to SSD approximation can be explicitly included

Coello Pérez, Menéndez and Schwenk, PRC 98, 045501 (2018)

- subsequently decay to first excited 0^+_2 can be predicted

Coello Pérez, Menéndez and Schwenk, PRC 98, 045501 (2018)

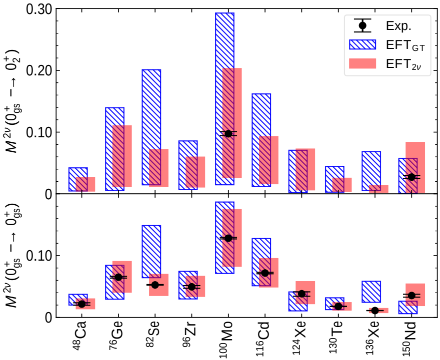
$$M^2_{\mathrm{EFT}}(0^+_{\mathrm{gs}}\ !\ 0^+_2) \quad \left(1+\frac{D_{10^+_2}}{D_{20^+_2}}+\frac{D_{10^+_2}}{D_{30^+_2}}\right)\frac{D_{10^+_{\mathrm{gs}}}}{D_{10^+_2}}\frac{p\overline{2}}{3}M^2_{\mathrm{EFT}}(0^+_{\mathrm{gs}}\ !\ 0^+_{\mathrm{gs}})$$

$$(\mathrm{gs}\ !\ 0^+_2) = \frac{!}{}\left(\frac{D_{10^+_2}}{D_{20^+_2}}+\frac{D_{10^+_2}}{D_{30^+_2}}\right)+\frac{D_{10^+_2}}{}\left(\frac{!}{};1;\frac{D_{30^+_2}+\ !}{!}\right)$$

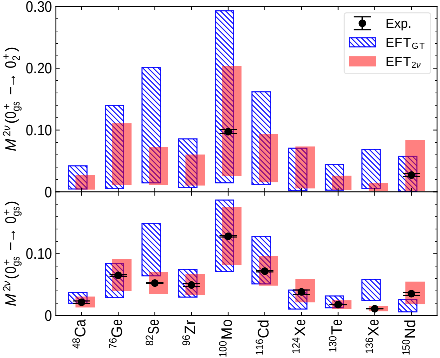
fit to GT data

- EFT works very well for gs to gs and for gs to exc(0_2^+)

- but for ^{136}Xe gs to gs not consistent with experiment



Jokiniemi, Romeo, CB, Kotila, Soriano, Schwenk and Menéndez arXiv:2211.03764 in press at PLB



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fit to GT data

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- but for ^{136}Xe gs to gs not consistent with experiment

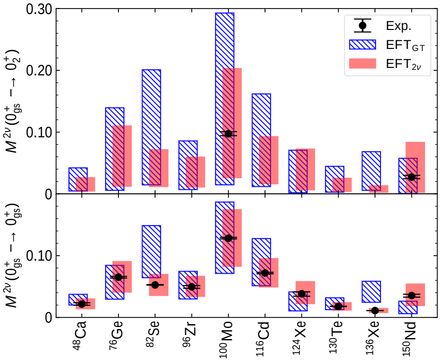
fit to -decay data

- fit directly to 2 data ! gs to gs agreement perfect by construction

Results

fit to GT data

- EFT works very well for gs to gs and for gs to exc(0_2^+)
- but for ^{136}Xe gs to gs not consistent with experiment



Jokiniemi, Romeo, CB, Kotila, Soriano, Schwenk and Menéndez arXiv:2211.03764 in press at PLB

fit to -decay data

- fit directly to 2 data ! gs to gs agreement perfect by construction

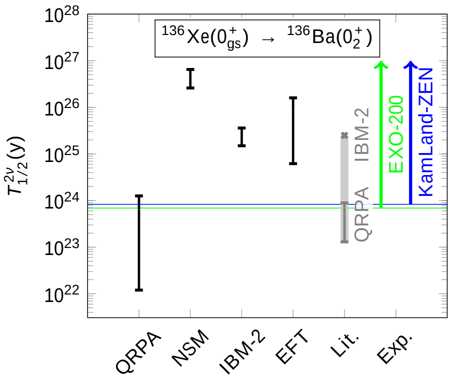
comparison

- fit to 2 : NMEs generally smaller
- overlap of fitting strategies: smallest for ^{136}Xe

Results: comparison with predictions from other methods

half-lives!

- EFT advantage: systematic theoretical uncertainties
- QRPA only small overlap with lower limits
- NSM, IBM-2 and EFT in complete agreement with exp. lower limit
- IBM-2 and EFT consistent



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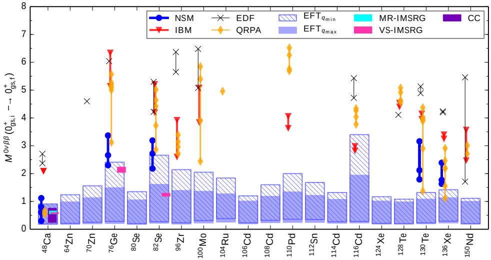
So I am excited about future experimental measurements

Summary

Summary

- rare decays within EFT for heavy nuclei at LO
- in general: 0 EFT NMEs smaller in comparison
- consistent with *ab initio* calculations



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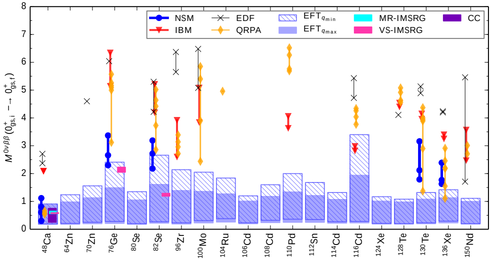

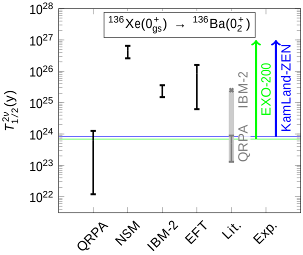

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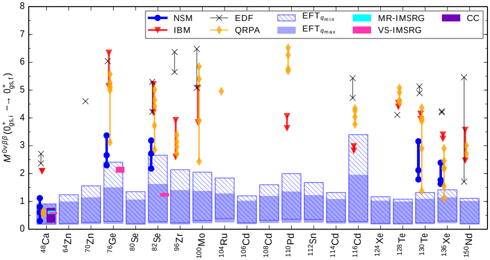

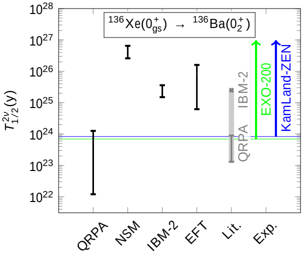

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Thank you!!