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

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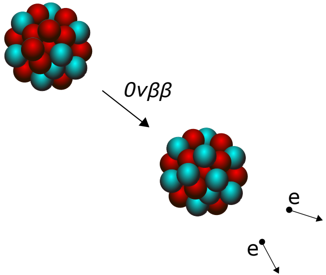
Workshop on Progress in *Ab Initio* Nuclear Theory



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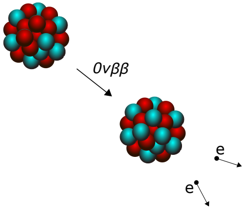
$0\nu\beta\beta$ decay

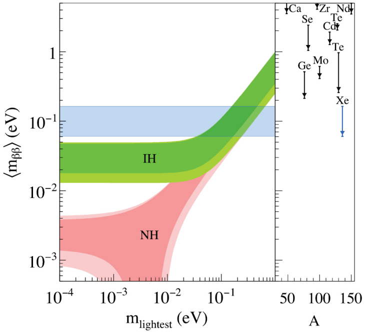


- lepton-number violation: no ν-emission
  - $\rightarrow$ insights to matter and anti-matter asymmetry
  - $\rightarrow$ BSM physics
- ν: neutral and massive
  - $\rightarrow$ Majorana ($\nu = \overline{\nu}$) or Dirac ($\nu \neq \overline{\nu}$) particles?

open questions

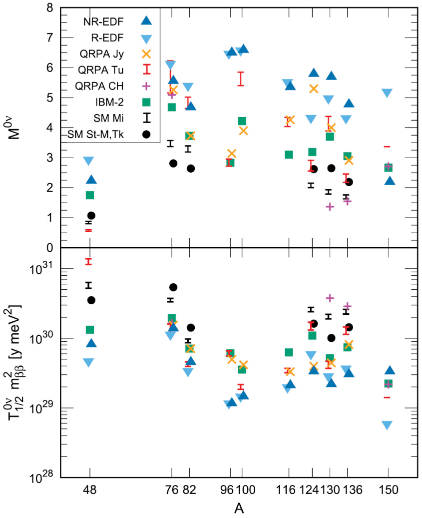
- mechanism(s) governing $0\nu\beta\beta$ decay
- mass hierarchy of neutrinos

answering these questions can be hindered by uncertainty of NMEs



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

Motivation



- 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:
current uncertainty estimation
→ variation of model parameters

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

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

$$[d_\mu, d_\nu^\dagger] = \delta_{\mu\nu} \,, \quad \{n_\mu, n_\nu^\dagger\} = \delta_{\mu\nu} \,, \quad \{p_\mu, p_\nu^\dagger\} = \delta_{\mu\nu}$$

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

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

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

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

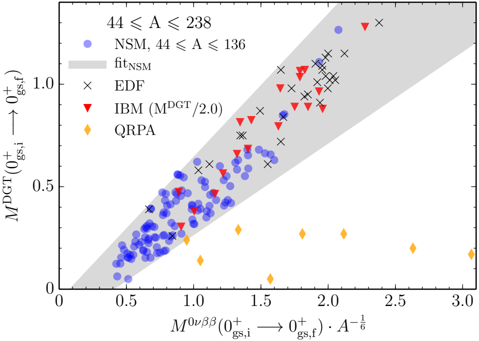
$0\nu\beta\beta$ not observed - how to fit low-energy constants?

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

strategy:

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

$\rightarrow$ EFT $0\nu\beta\beta$ NME prediction with systematic quantified uncertainties



LO nuclear matrix element

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

LO nuclear matrix element - Low-energy constant

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

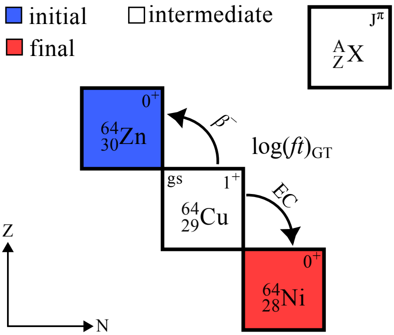
$\overline{C}^2_\beta$ fit to GT data: $\quad \bar{C}^2_\beta = C_{\beta 1} C_{\beta 2}$

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

- GT transition selection rule:

  $\triangle J_{\mathrm{GT}} = 1 \quad \triangle \pi_{\mathrm{GT}} = +$

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

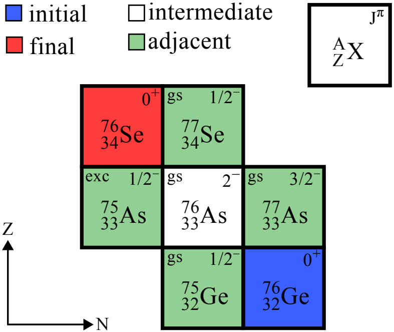


https://www.nndc.bnl.gov/ensdf/ ,
Grewe *et al.*, Phys. Rev. C 76, 054307 (2007), Thies *et al.*, Phys. Rev. C 86, 014304 (2012)
Frekers *et al.*, Phys. Rev. C 94, 014614 (2016), Thies *et al.*, Phys. Rev. C 86, 054323 (2012)
Puppe *et al.*, Phys. Rev. C 86, 044603 (2012), Puppe *et al.*, Phys. Rev.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

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

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

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



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

Nucleon orbitals

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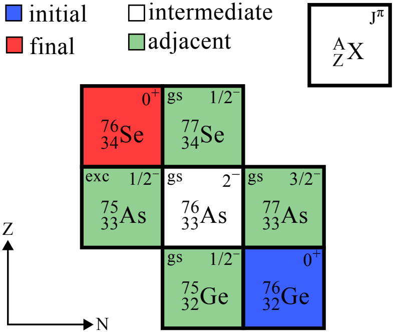

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DGT NME + correlation band → $0\nu\beta\beta$ NME

Predictions in comparison

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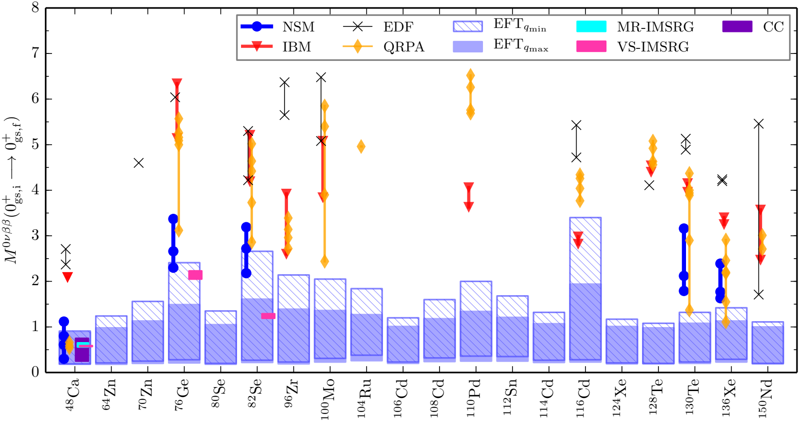

Menéndez *et al.*, Nucl. Phys. A 818, 139 (2009), Horoi *et al.*, Phys. Rev. C 101, 044315 (2020), Iwata *et al.*, Phys. Rev. Lett. 116, 112502 (2016), Rodríguez *et al.*, Phys. Rev. Lett. 105, 252503 (2010), Song *et al.*, Phys. Rev. C 95, 024305 (2017), Šimkovic *et al.*, Phys. Rev. C 87, 045501 (2013), 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)

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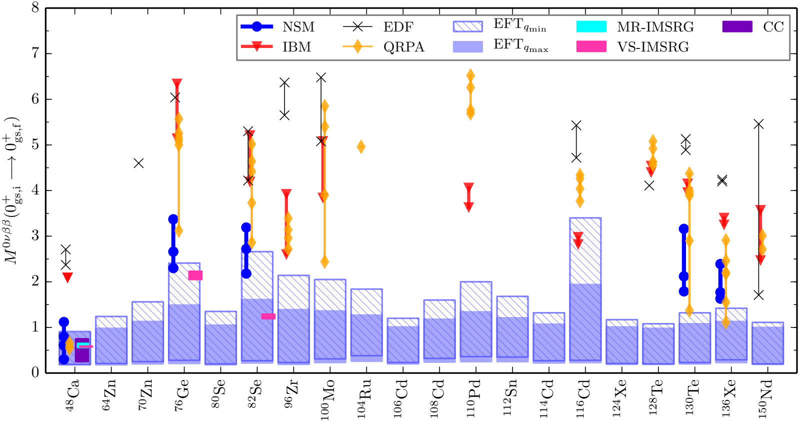
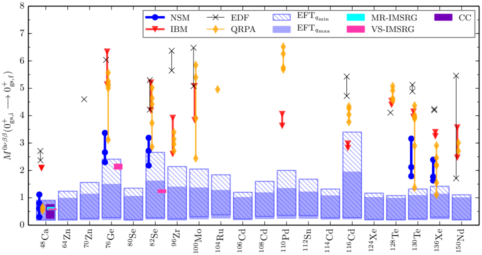


- range: $M^{0\nu\beta\beta}_{\mathrm{EFT}} \leqslant 3.40$ vs. $M^{0\nu\beta\beta}_{\mathrm{other}} \leqslant 6.5$ $\rightarrow$ EFT smaller predictions
- **(almost) overlap: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd and ^{136}Xe**
- combined unc. from other models larger than EFT unc.
- **consistent with *ab initio* predictions** (MR-/VS-IMSRG & CC)

Summary

- $0\nu\beta\beta$ decay within EFT for heavy nuclei at LO
- in general: $0\nu\beta\beta$ EFT NMEs smaller in comparison
- consistent with *ab initio* calculations



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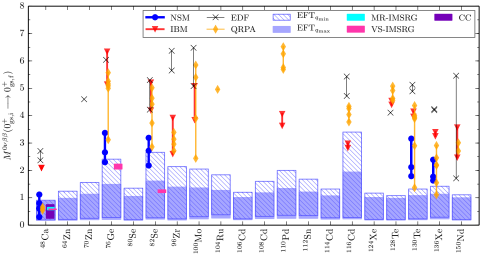

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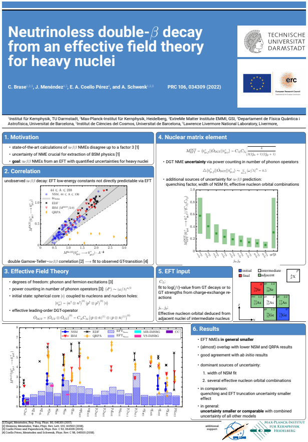

Thank you!!