Ab initio calculations of beta-decay half-lives for $N = 50$ neutron-rich nuclei

arXiv:2509.06812

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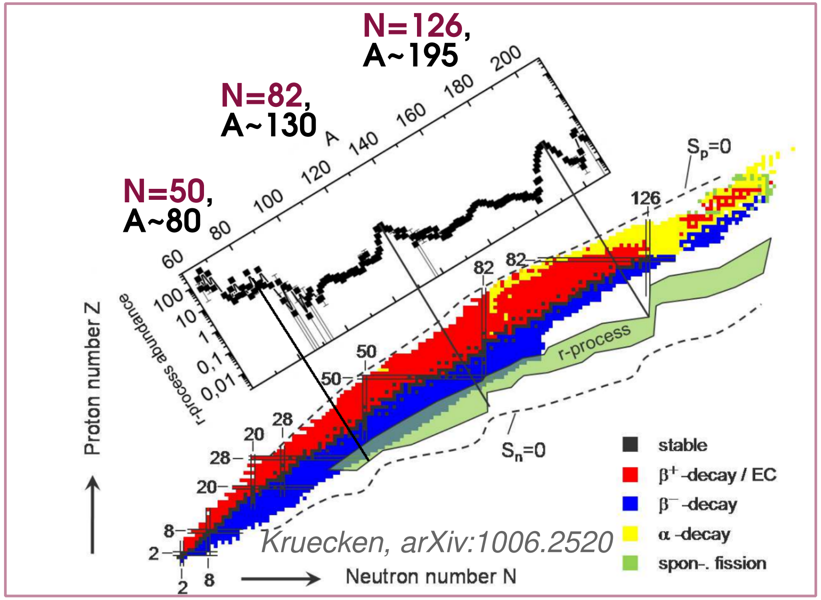
Beta decay half-lives for *r*-process



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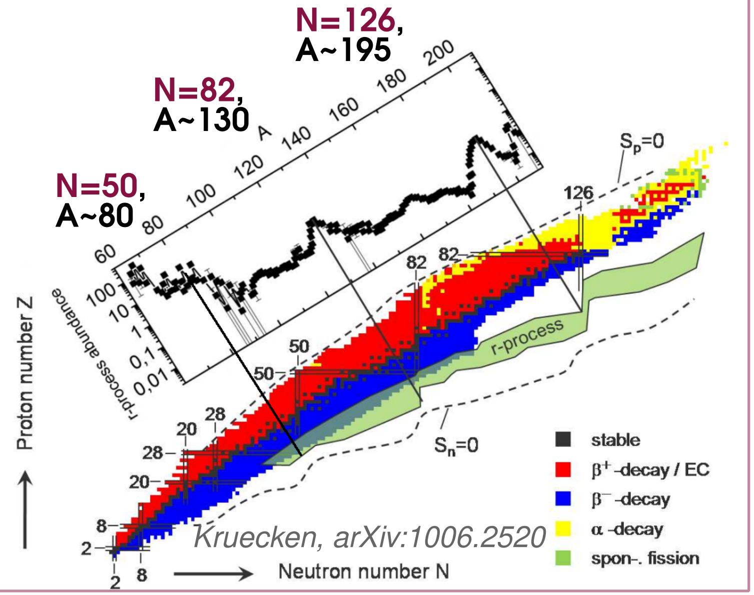
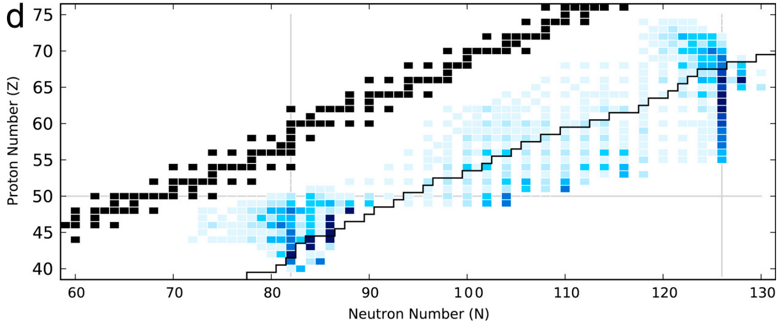


***r*-process sensitivity to nuclear beta decay:**



Mumpower et al., PPNP 86 (2016) 86

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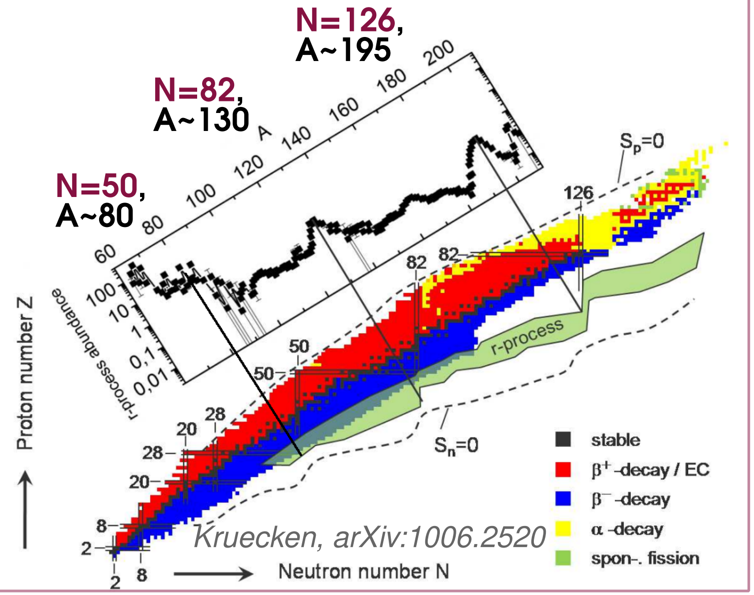
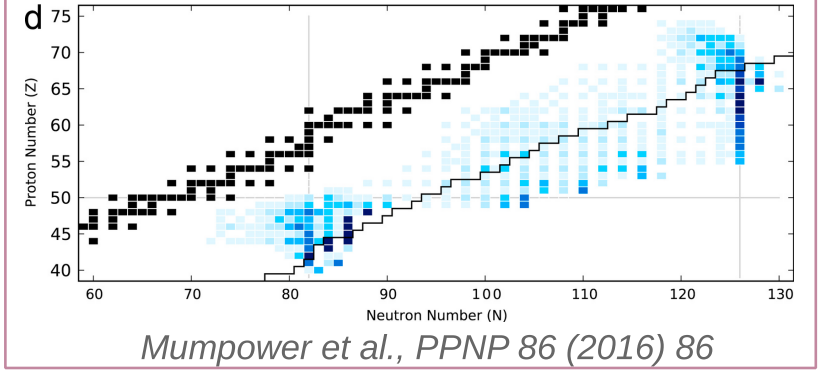


r-process sensitivity to nuclear beta decay:



Very active area in experiment:

N~50: NSCL@MSU: PRL 94 (2005) 112501; PRC 82 (2010) 025806; RIKEN: PRL 113 (2014) 032505; PRL 134 (2025) 172701; ...

N~82: RIKEN: PRL 114 (2015) 192501; ISOLDE@CERN: PRC 104 (2021) 044328; PRL 131 (2023) 022501; ...

N~126: GSI: PRL 117 (2016) 012501; ...

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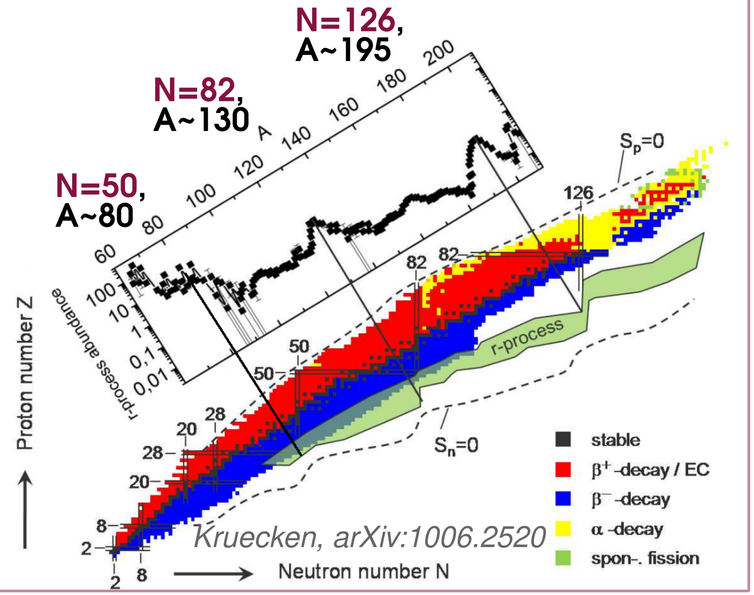

Kruecken, arXiv:1006.2520

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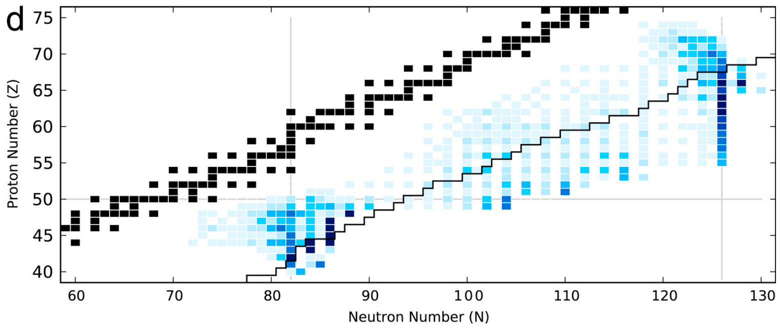

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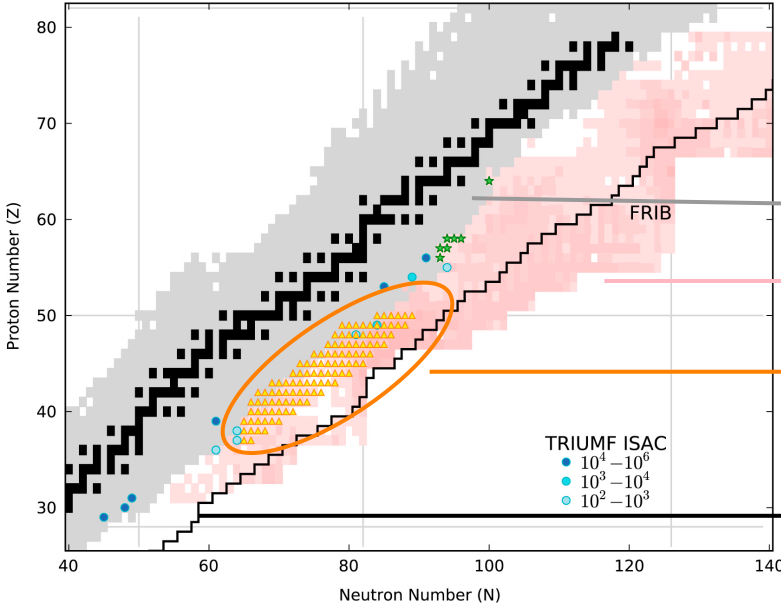


Still less known experimentally!

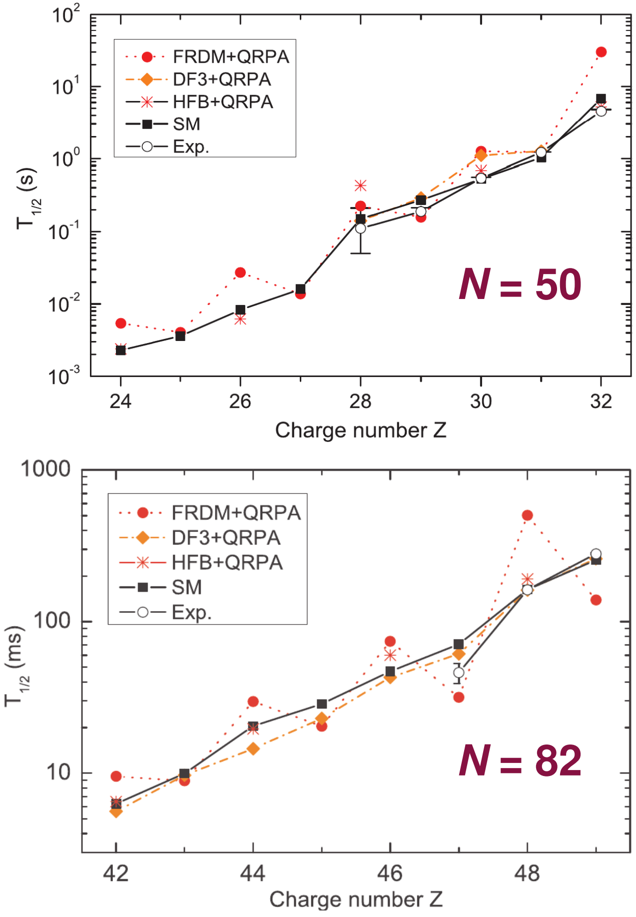
AME2012

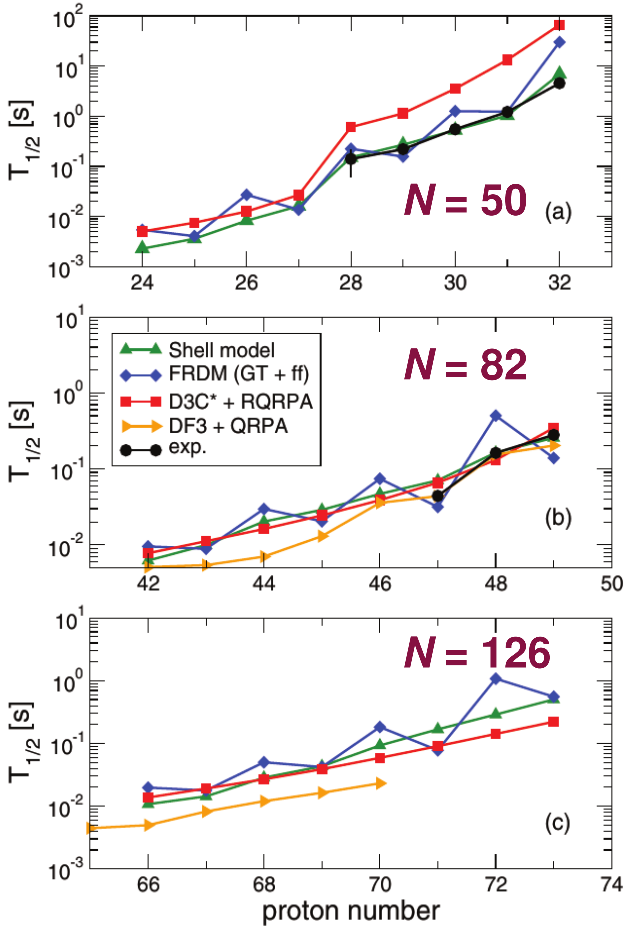
Needed for r-process simulations

RIKEN experiments

Estimated capabilities at FRIB (10^{-4} pps)

Motivation



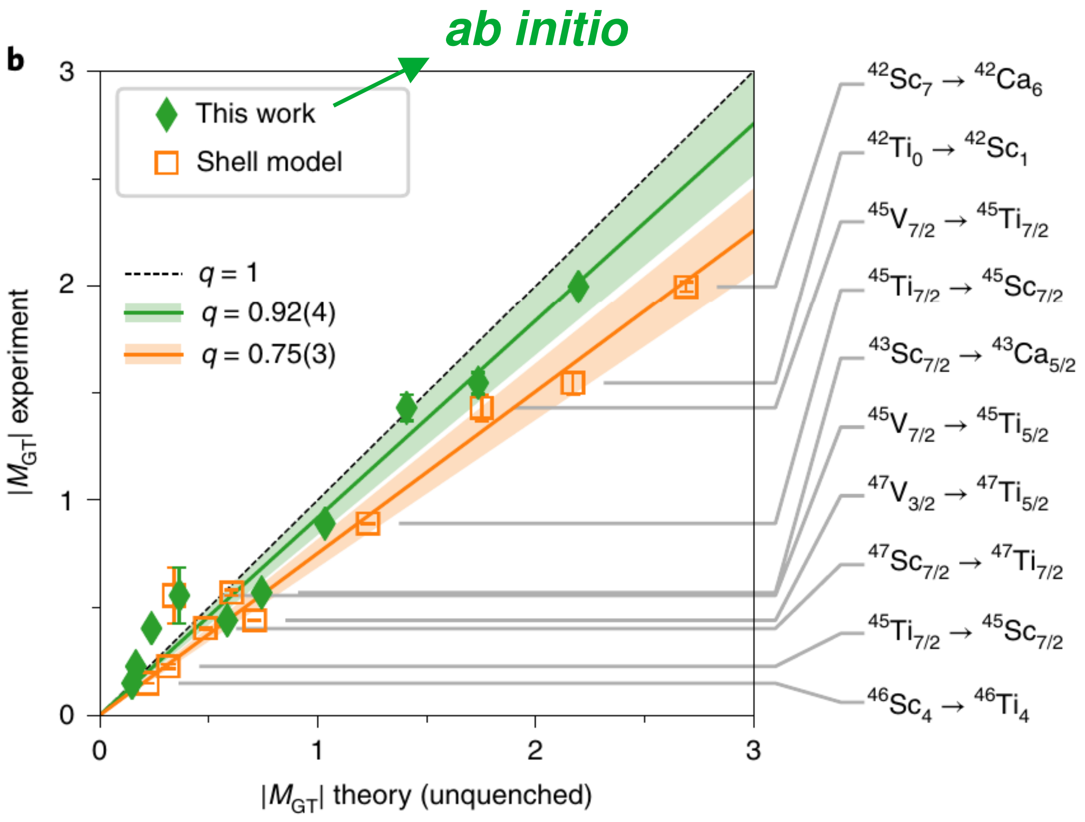


- Neutron-rich, less known experimentally
- Current model calculations show sizable discrepancies
- Quenched g_A (e.g., $g_A^{\text{eff}} \sim 0.8 g_A$) is used in current model calculations

Zhi et al., PRC 87 (2013) 025803

Marketin et al., PRC 93 (2016) 025805

Motivation



Gysbers et al., Nat. Phys. 15 (2019) 428

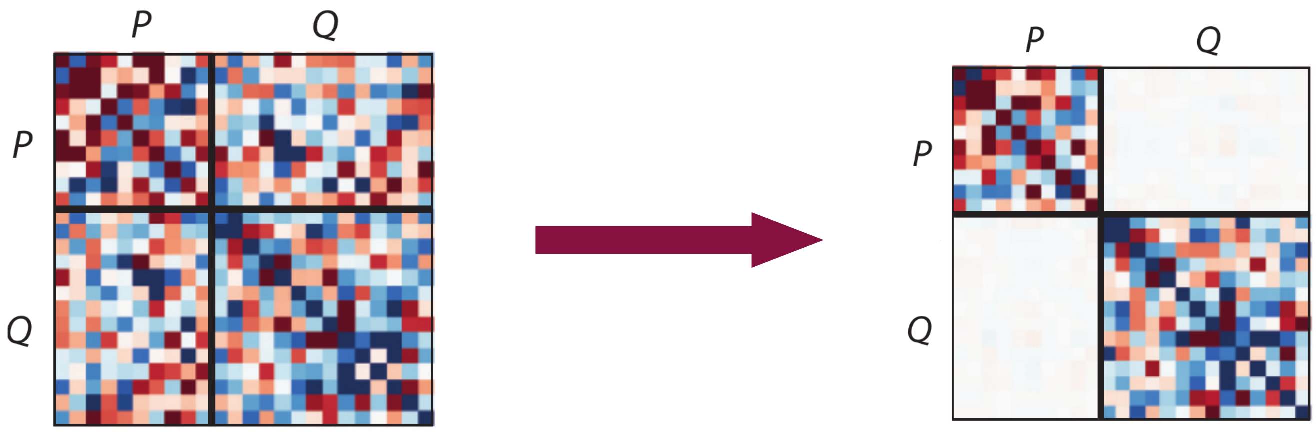
- ***Ab initio* calculations:**

  Quenching puzzle of g_A in Gamow-Teller (GT) transitions can be explained by taking into account *many-body correlations* and *two-body currents*

- **Our focus:**

  Ab initio calculations of beta-decay half-lives for N = 50 neutron-rich nuclei

Valence-space in-medium similarity renormalization group (VS-IMSRG)



$$H|\Psi_k\rangle = E_k|\Psi_k\rangle$$

$$H_{\text{eff}}|\Psi_k^P\rangle = E_k|\Psi_k^P\rangle$$

$$H = T + V_{\text{NN}} + V_{3\text{N}}$$

from Chiral EFT

$$\begin{aligned} H_{\text{eff}} &= [U(s)HU^\dagger(s)]_{s\to\infty} \\ \mathcal{O}_{\text{eff}} &= [U(s)\mathcal{O}U^\dagger(s)]_{s\to\infty} \end{aligned}$$

Tsukiyama, Bogner and Schwenk, PRL 106 (2011) 222502
Hergert at al., Phys. Rep. 621 (2016) 165
Stroberg et al., Ann. Rev. Nucl. Part. Sci. 69 (2019) 307

Total beta-decay half-life

- Total β^--decay half-life from initial ground state:

$$T_{1/2}^{-1} = \sum_f t_{fi}^{-1} \qquad t_{fi}^{-1} = \frac{1}{\kappa}\int_1^{W_0} C(W)F(Z,W)\sqrt{W^2-1}W(W_0-W)^2\mathrm{d}W$$

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- Gamow-Teller (GT) transition (dominates)

$$t_{fi}^{-1} = \frac{1}{\kappa}B(\mathrm{GT})f_0 \qquad C_{\mathrm{GT}}(W) = B(\mathrm{GT}) = \frac{1}{(2J_i+1)}|\langle \Psi_f(J_f)||\mathrm{GT}||\Psi_i(J_i)\rangle|^2$$

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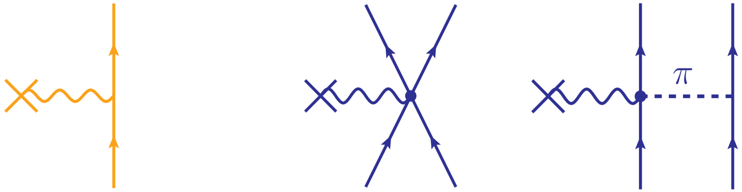
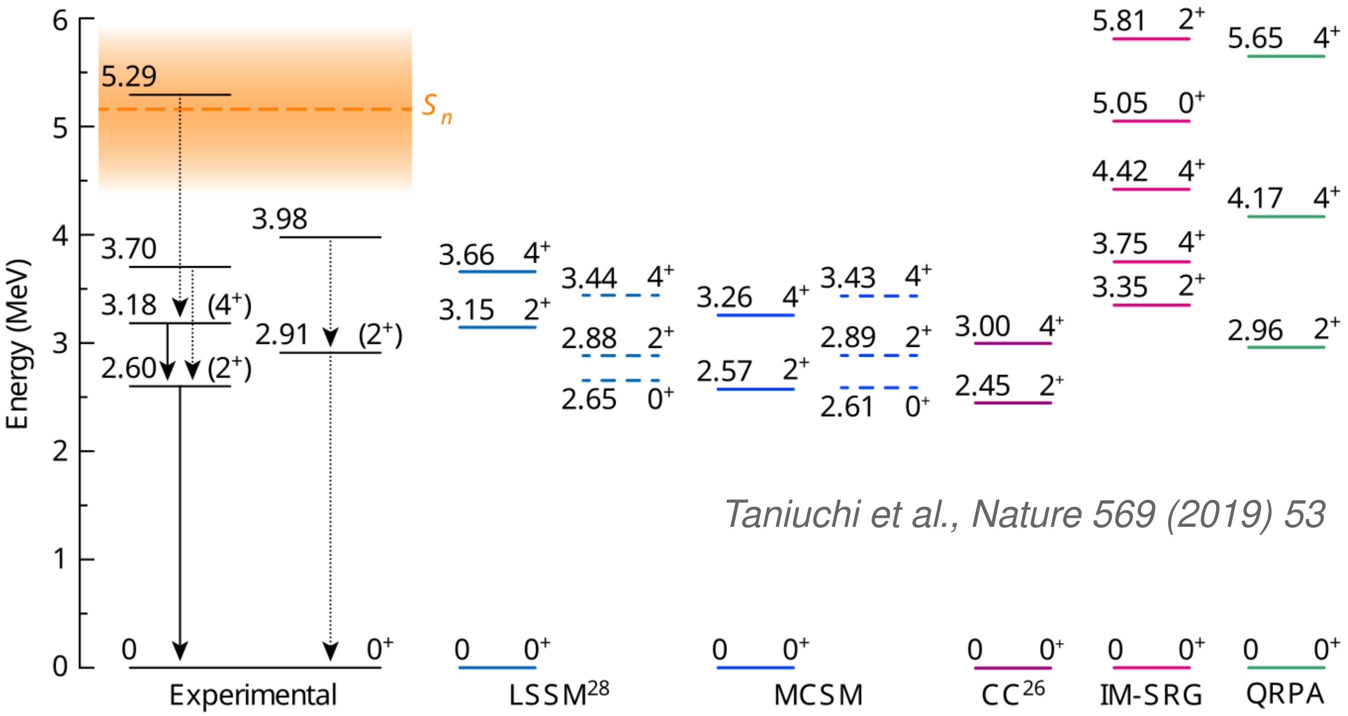
$$\mathrm{GT} = \mathrm{GT}_{1\mathrm{B}} + \mathrm{GT}_{2\mathrm{B}} \qquad f_0 = \int_1^{W_0} F(Z,W)\sqrt{W^2-1}W(W_0-W)^2 \mathrm{d}W$$



$$\mathrm{GT}_{1\mathrm{B}} = \sum_{k=1}^{A} g_A \boldsymbol{\sigma}_k \tau_k^- \qquad \mathrm{GT}_{2\mathrm{B}} = \sum_{i<j}^{A} \mathbf{j}_{ij}^-$$ from chiral EFT

Park et al., PRC 67 (2003) 055206
Menéndez, Gazit and Schwenk, PRL 107 (2011) 062501
Hoferichter, Menéndez and Schwenk, PRL 102 (2020) 074018
Krebs, EPJA 56 (2020) 234

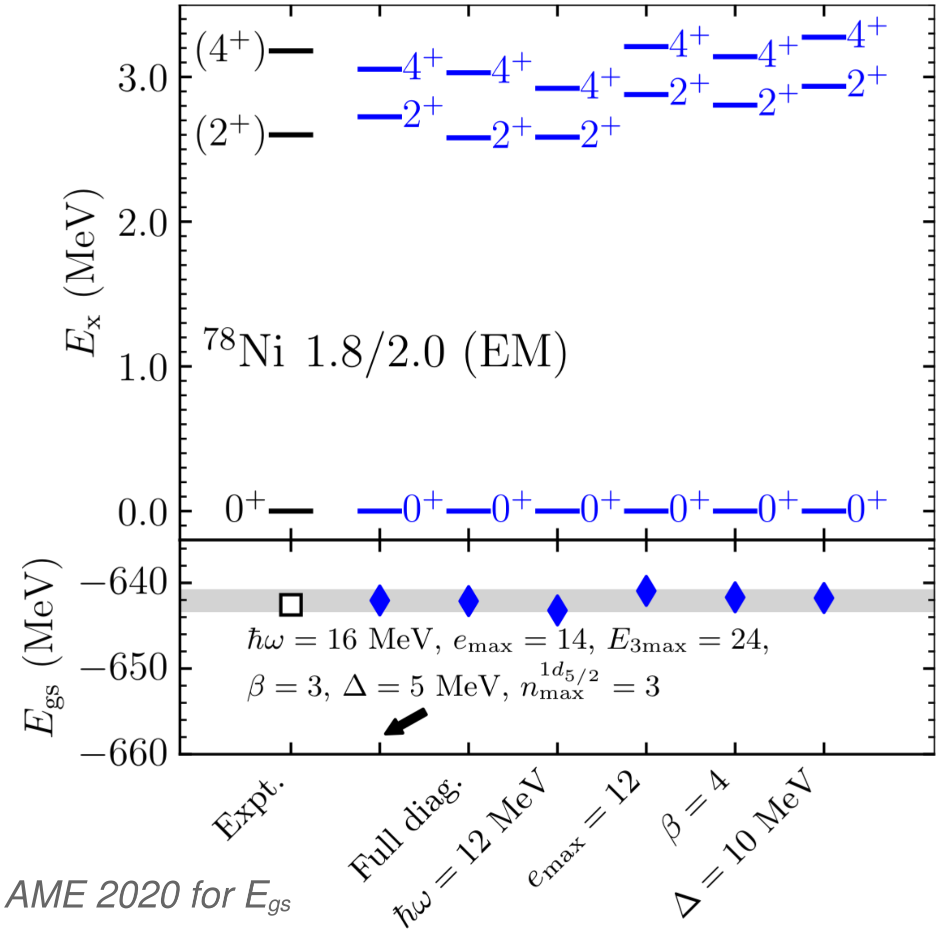
Spectra of ^{78}Ni



Taniuchi et al., Nature 569 (2019) 53

VS-IMSRG: core ^{60}Ca, proton valence space *pf*-shell, neutron valence space *sdg*-shell

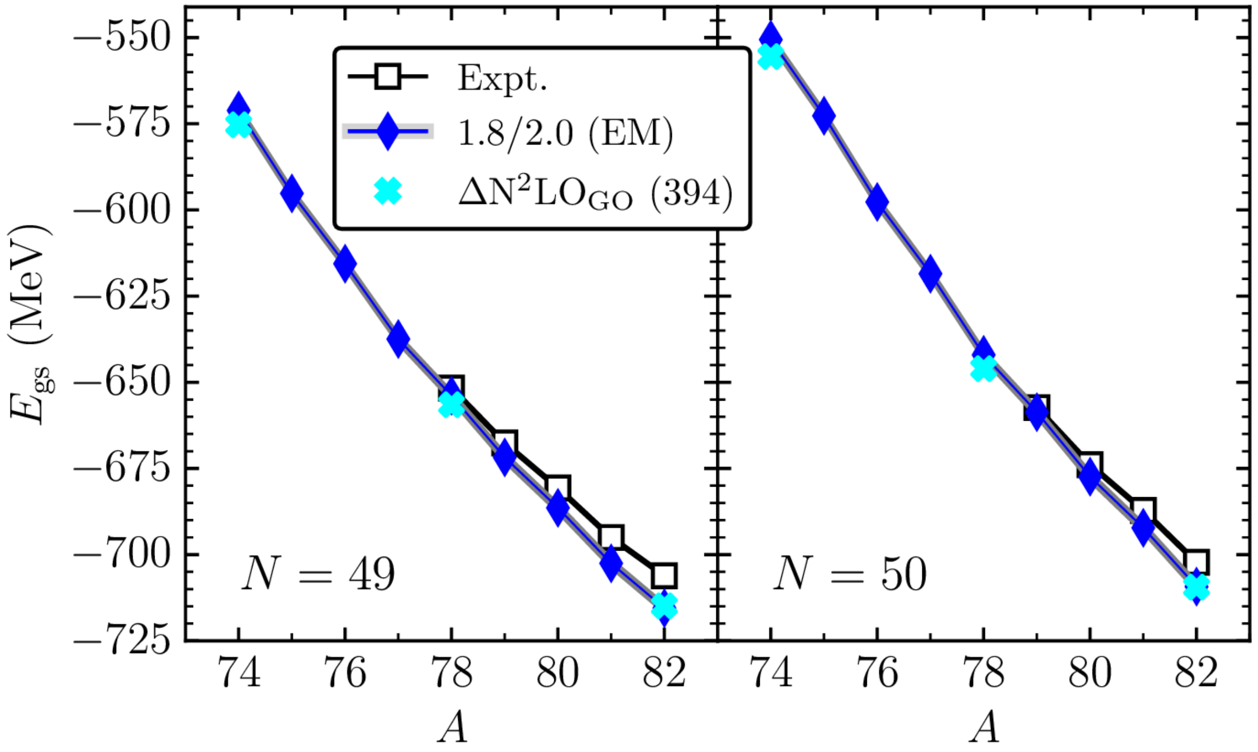
Results for ^{78}Ni



AME 2020 for E_{gs}

- NN+3N interaction: 1.8/2.0 (EM) from *Hebeler et al., PRC 83 (2011) 031301*
- ^{48}Ca+$\{0f^p_{7/2,5/2}, 1p^p_{3/2,1/2}, 0f^n_{5/2}, 1p^n_{3/2,1/2}, 0g^n_{9/2}, 1d^n_{5/2}\}$
- Small uncertainty from the model space parameters (e.g., E_{gs} spans the gray band $\sim$ 2.3 MeV)
- From now on: $\hbar\omega$ = 16 MeV, e_{max} = 14, E_{3max} = 24, β = 3, Δ = 5 MeV, $n_{max}^{1d_{5/2}}$ = 3

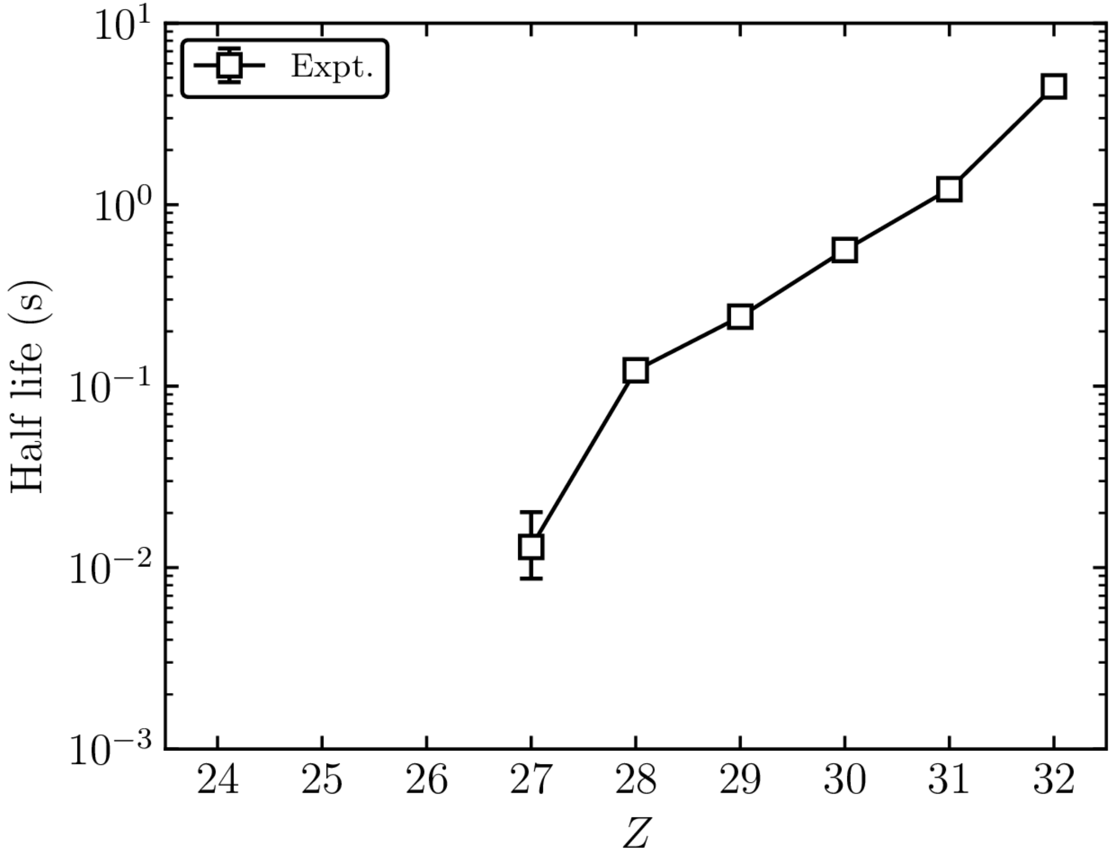
Ground-state energies



- Ground-state energies are slightly overestimated (by 1% for the worst case)

Expt.: https://www.nndc.bnl.gov
NN+3N interaction: ΔN^2LO_{GO} (394) from Jiang et al., PRC 102 (2020) 054301

Total beta-decay half-lives from GT transitions



Expt.: Xu et al., PRL 113 (2014) 032505; https://www.nndc.bnl.gov

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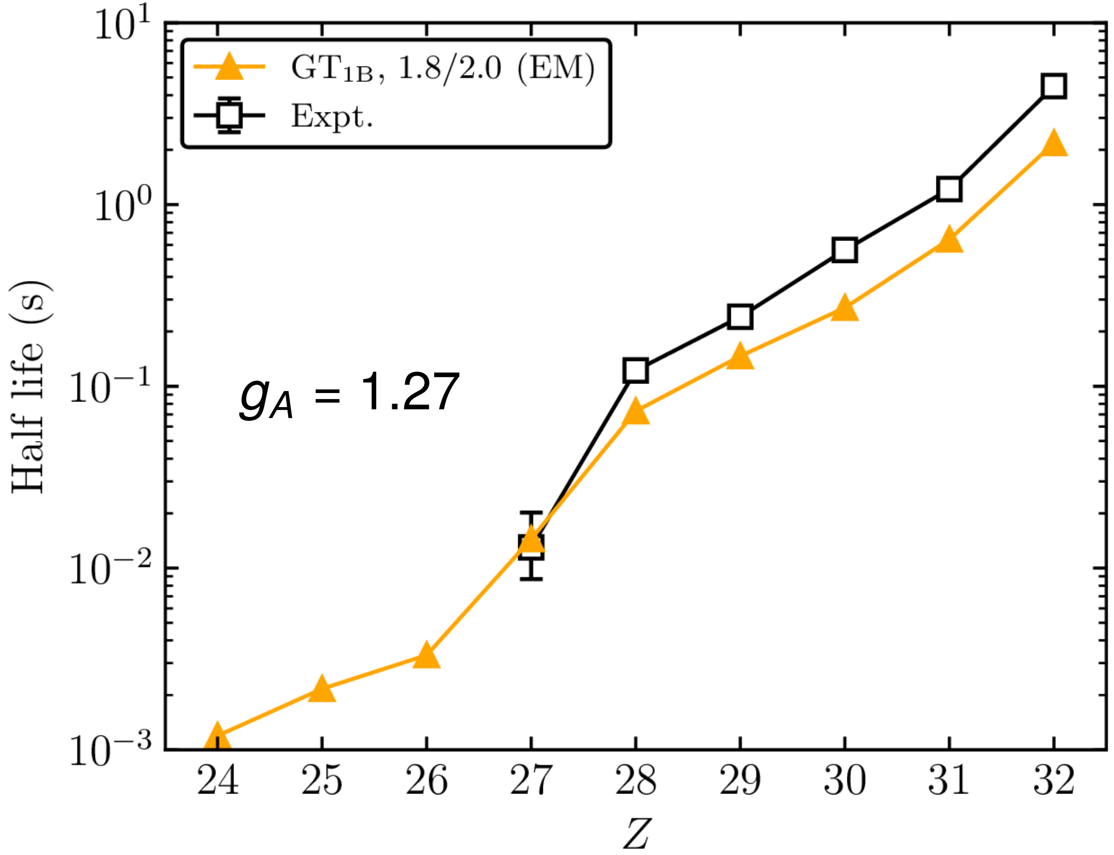

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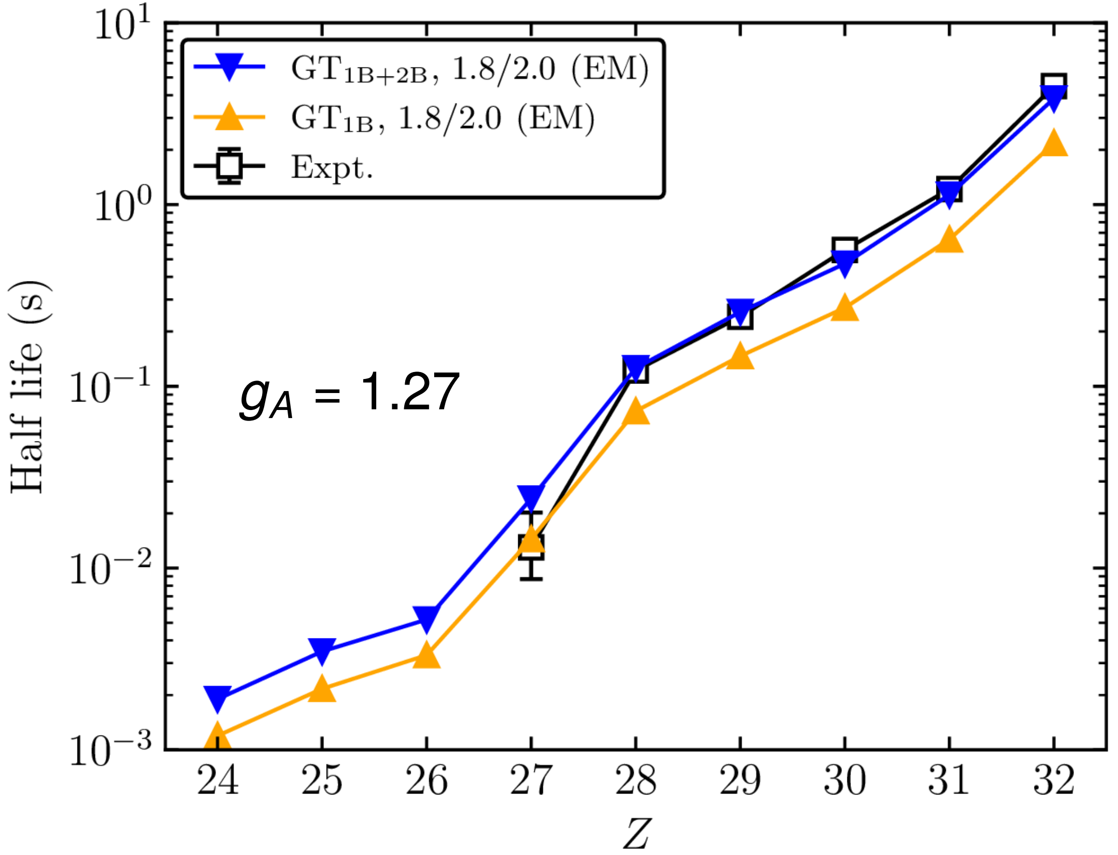
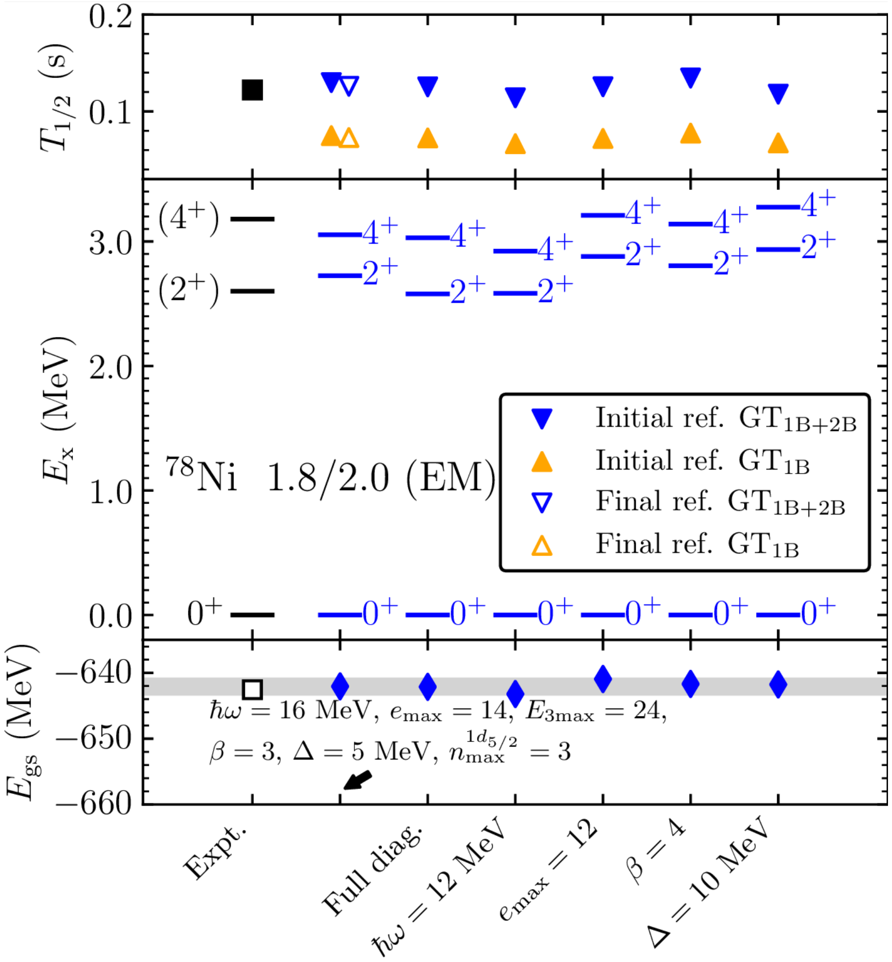


Expt.: Xu et al., PRL 113 (2014) 032505; https://www.nndc.bnl.gov

From unquenched g_A!

Total beta-decay half-lives from GT transitions



Expt.: Expt.: Taniuchi et al., Nature 569 (2019) 53; Xu et al., PRL 113 (2014) 032505; https://www.nndc.bnl.gov

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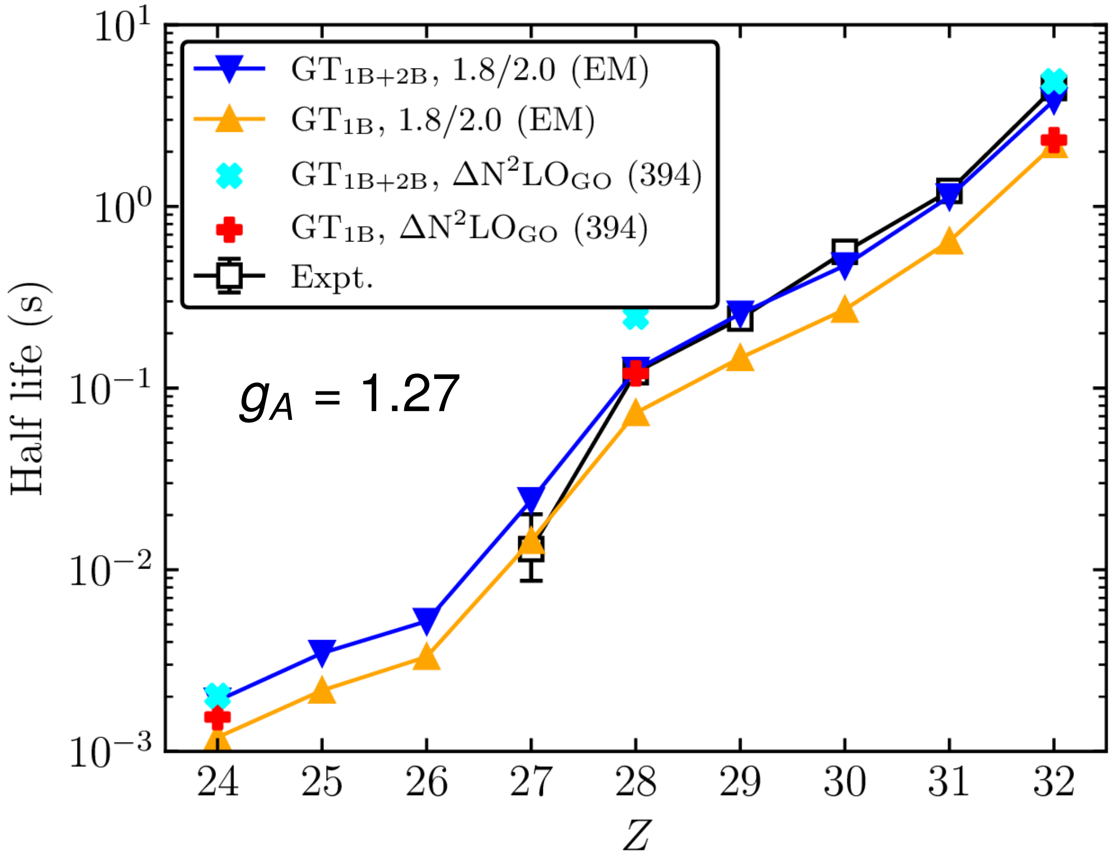
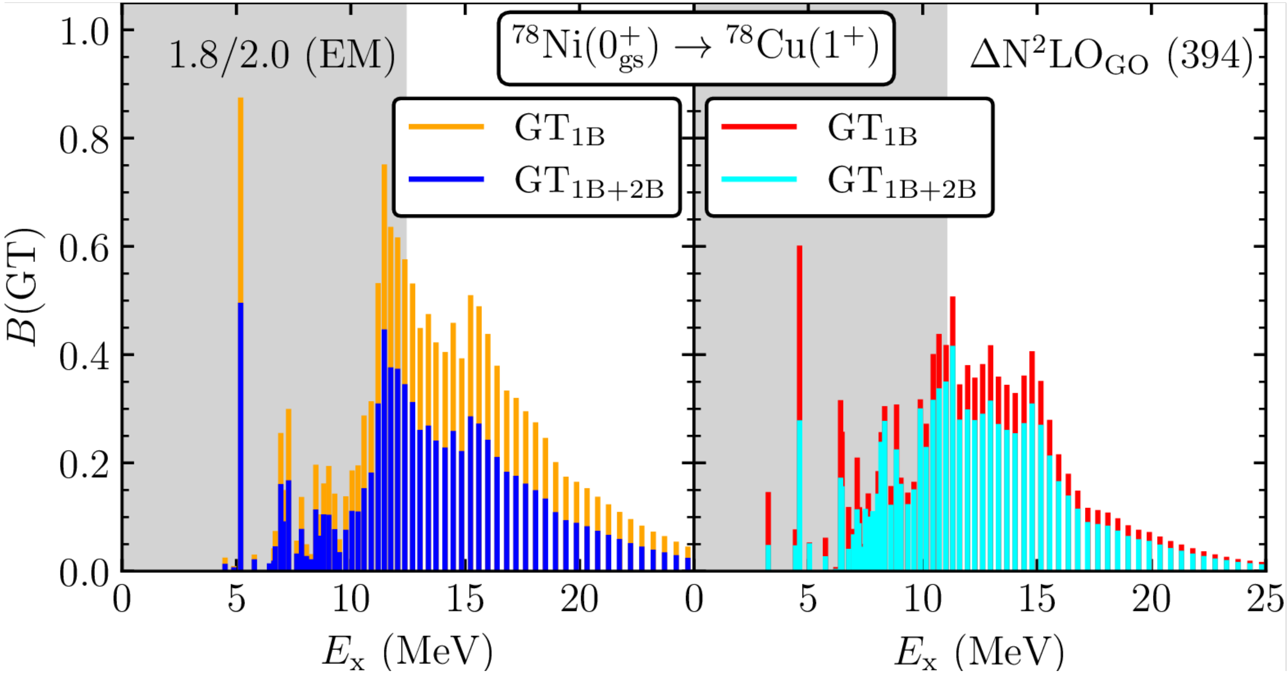


Expt.: Xu et al., PRL 113 (2014) 032505; https://www.nndc.bnl.gov

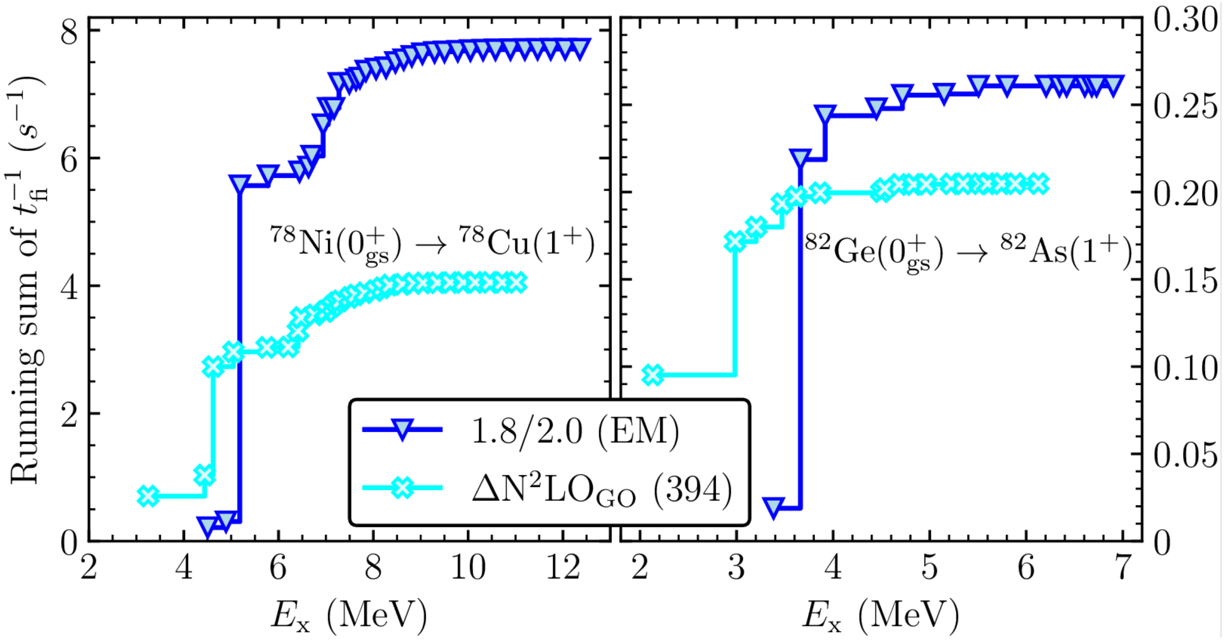
- Two-body currents improve the predicted half-lives significantly
- Two-body currents have similar effect as quenching g_A, i.e., reducing transition strength and therefore increasing the half-life

GT transition strength distribution for ^{78}Ni



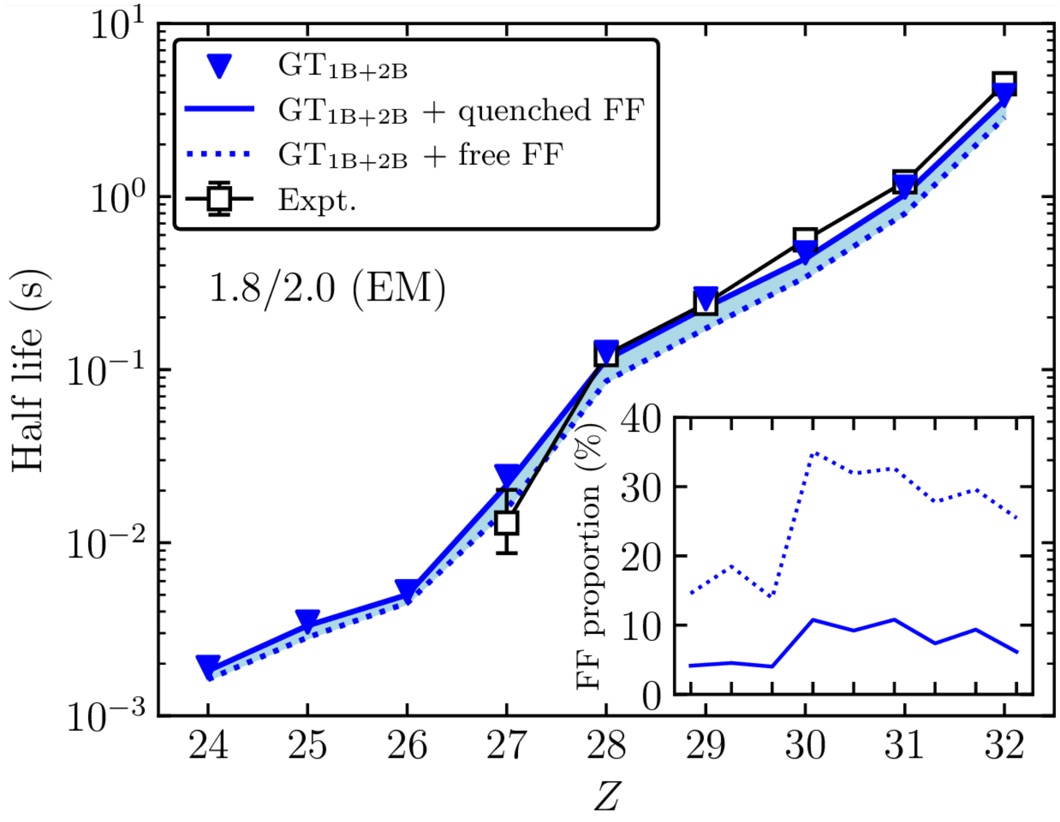
- Including 2B currents → systematically reduced transition strength distribution
- *B*(GT) distribution is quite different between 1.8/2.0 (EM) and ΔN^{2}LO$_{GO}$ (394)

Running sum of t^{-1} for ^{78}Ni and ^{82}Ge



- Inverse of total half-life $T_{1/2}^{-1} = \sum_f t_{fi}^{-1}$, where $t_{fi}^{-1} = B(\mathrm{GT}) f_0/\kappa$
- f_0 is quite different between 1.8/2.0 (EM) and ΔN^{2}LO$_{GO}$ (394) for both ^{78}Ni and ^{82}Ge
- Surprisingly close final running sums from 1.8/2.0 (EM) and ΔN^{2}LO$_{GO}$ (394) for ^{82}Ge

Contribution from first forbidden (FF) transitions



GT: g_A = 1.27

FF: $C_{FF}(W) = k + kaW + kb/W + kcW^2$

9 operators in C_{FF}

FF quenching factors:

Zhi et al., PRC 87 (2013) 025803

Small proportion of FF transition (<11%) with quenched FF operators

Blue band: our final prediction

Expt.: Xu et al., PRL 113 (2014) 032505; https://www.nndc.bnl.gov

Summary and outlook

- Summary
  - First *ab initio* calculations of total β-decay half-lives of r-process waiting point nuclei at $N = 50$
  - Very good agreement with existing experimental data
  - Two-body currents play an important role
  - No need to use quenching factor in *ab initio* calculations
- Outlook
  - Quantify uncertainty especially from the Hamiltonian
  - Introduce 2BC into the FF transitions and construct effective FF operators within VS-IMSRG
  - Perform calculations for heavier r-process waiting point nuclei, e.g., at $N = 82$, $N = 126$

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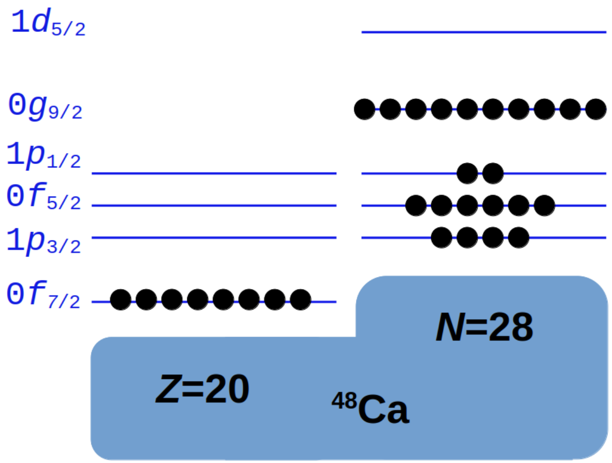
Thank you for your attention

Calculational setup for N = 50 isotones

- "Magic" 1.8/2.0 (EM) with NN + 3N interactions, consistent 2B currents
- Hartree-Fock basis $\hbar\omega$ = 16 MeV, $e_{\max} \equiv (2n + l)_{\max}$ = 14, $E_{3\max} \equiv (e_1 + e_2 + e_3)_{\max}$ = 24
- VS-IMSRG(2), NO2B approximation with ensemble reference
- P: core ^{48}Ca + valence space
  $\{0f^p_{7/2,5/2}, 1p^p_{3/2,1/2}, 0f^n_{5/2}, 1p^n_{3/2,1/2}, 0g^n_{9/2}, 1d^n_{5/2}\}$
- Arctangent (White) generator with Δ = 5 MeV
- $H' = H + \beta H_{\mathrm{cm}}$, $\beta = 3$
- Effective Hamiltonian $H_{\mathrm{eff}} = [U(s)H'U^\dagger(s)]_{s\to\infty}$
- Reference state from initial nucleus to evolve GT operator $\mathrm{GT}_{\mathrm{eff}} = [U(s)\mathrm{GT}U^\dagger(s)]_{s\to\infty}$
- Lanczos strength function method in the calculation of total GT transition probability



1.8/2.0 (EM): Hebeler et al., PRC 83 (2011) 031301;
Multi-shell valence space: Miyagi et al., PRC 102 (2020) 034320;
VS-IMSRG(2): Stroberg et al., PRL 118 (2017) 032502
Lanczos strength function: Haxton et al., PRC 72 (2005) 065501