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Study of single-β and $2\nu\beta\beta$ decays within an effective theory for collective nuclei

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Outline

Even-even nuclei

- Effective Hamiltonian and power counting
- E2 properties

Odd-mass nuclei

- Power counting for fermion operators
- Spectra at NNLO
- E2 and M1 properties

β decays from odd-odd nuclei

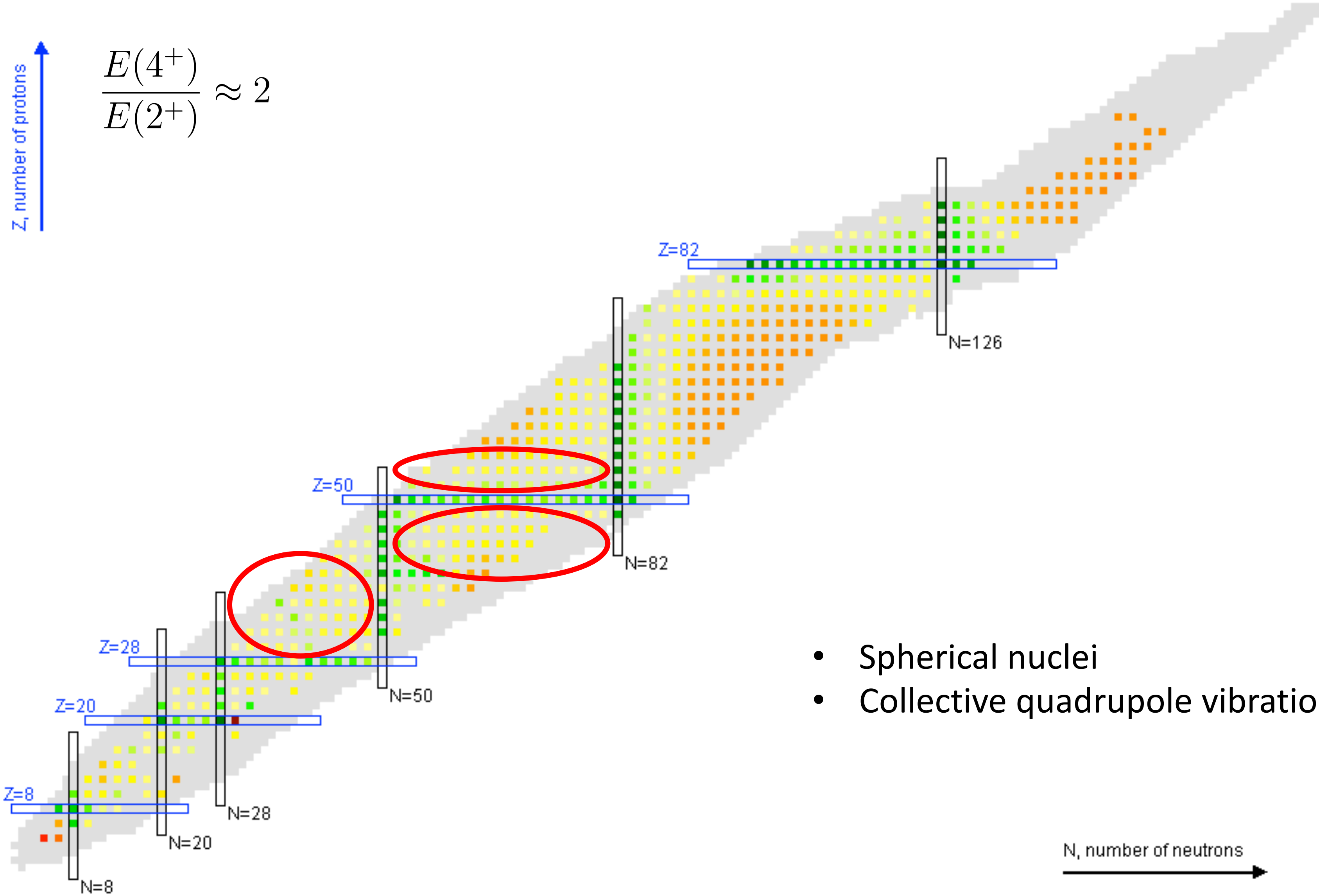
- Low-lying odd-odd states
- Effective Gamow-Teller operator
- Uncertainty estimates

$\beta\beta$ decays in the SSD approximation

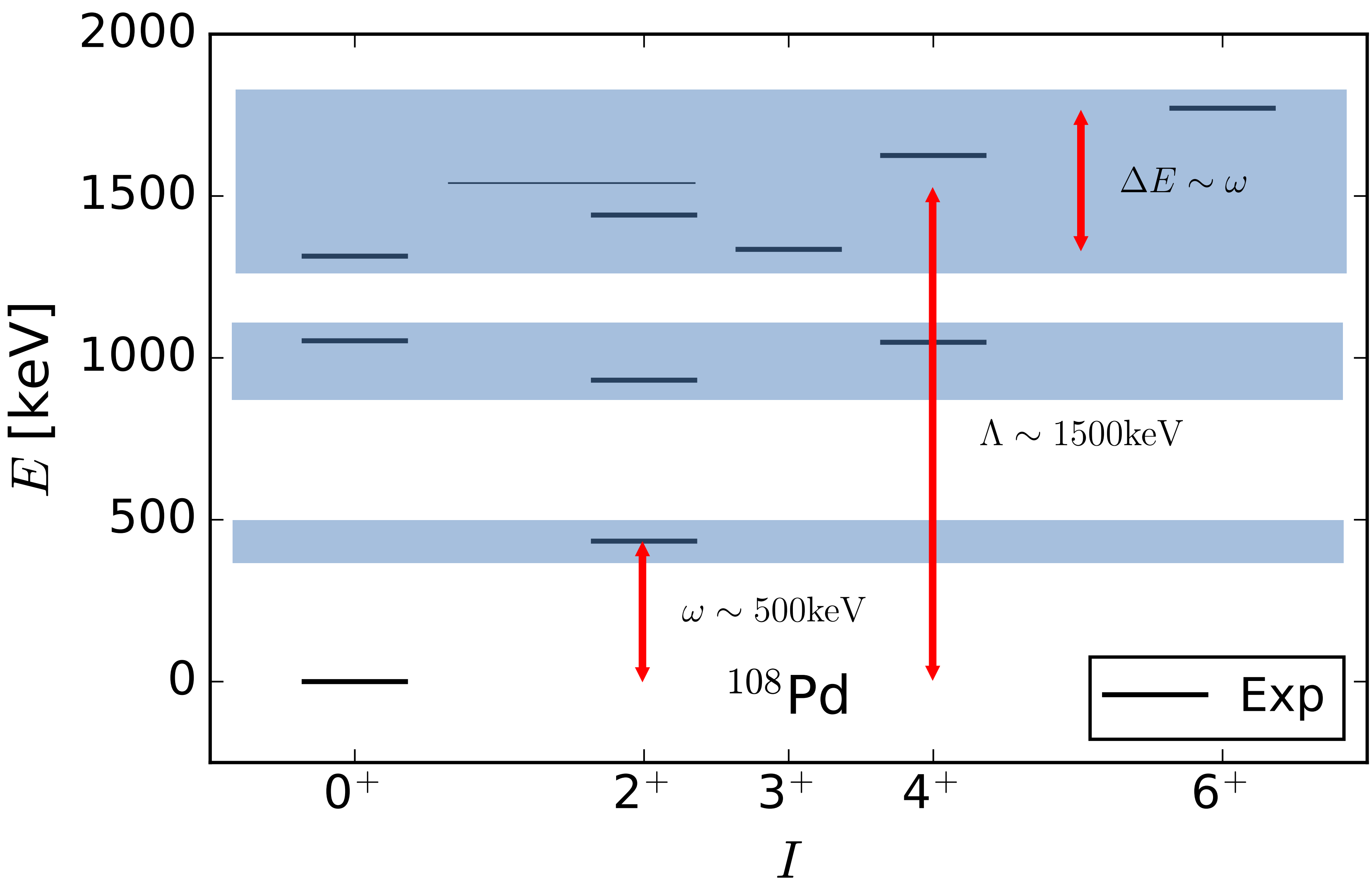
- Uncertainty estimate

Spherical nuclei

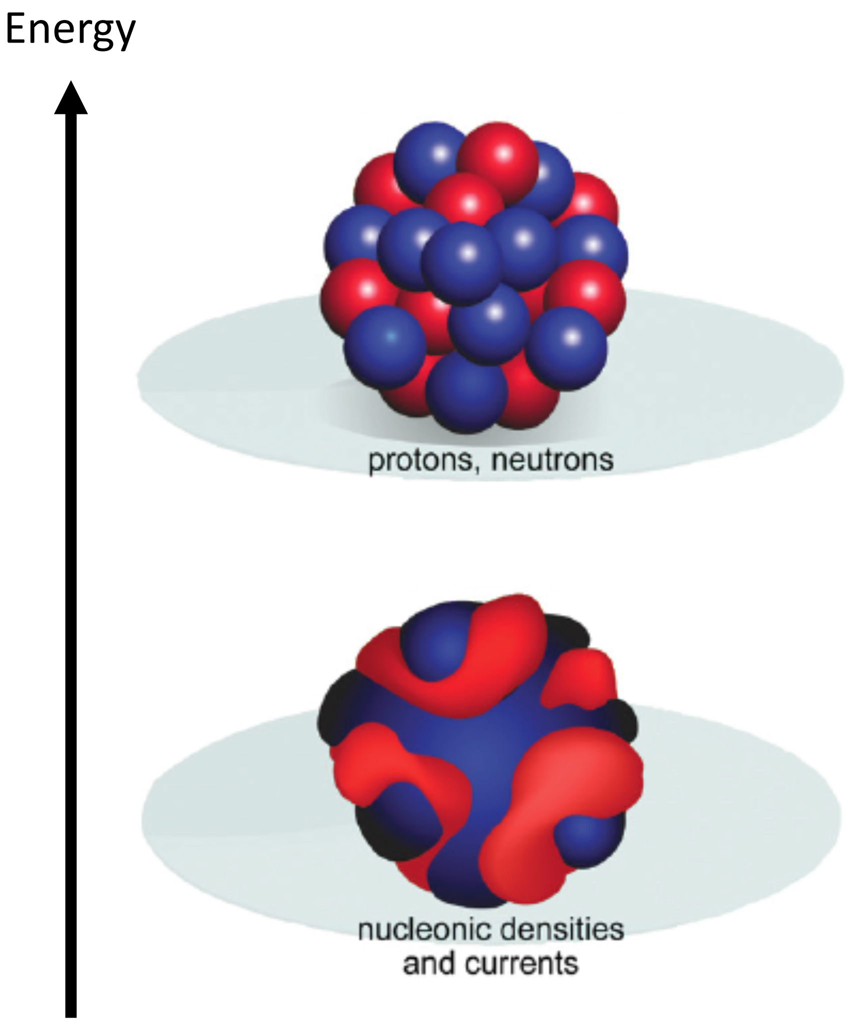
$$\frac{E(4^+)}{E(2^+)} \approx 2$$



- Spherical nuclei
- Collective quadrupole vibrations


2000
1500
1000
500
0
E [keV]
$\Delta E \sim \omega$
$\Lambda \sim 1500\text{keV}$
$\omega \sim 500\text{keV}$
^{108}Pd
Exp
0^+
2^+
3^+
4^+
6^+
I

Effective field theory for collective nuclei



Chiral EFT

- Nucleon and pion fields

Pionless EFT

- Nucleon fields

BREAKDOWN SCALE $\Lambda \sim 1500\mathrm{keV}$

$$\frac{\omega}{\Lambda} \ll 1$$

Collective EFT

- Phonons
- Few fermions

$\omega \sim 500\mathrm{keV}$

Bertsch, Dean, Nazarewicz, SciDAC Rev. **6**, 42 (2007)

Degrees of freedom: quadrupole-boson creation and annihilation operators

$$\left[d_\mu, d_\nu^\dagger\right] = \delta_{\mu\nu},$$

Rank-two tensors

$$d_\mu^\dagger \quad \text{and} \quad \tilde{d}_\mu = (-1)^\mu d_{-\mu}$$

Most simple rotational-invariant Hamiltonian

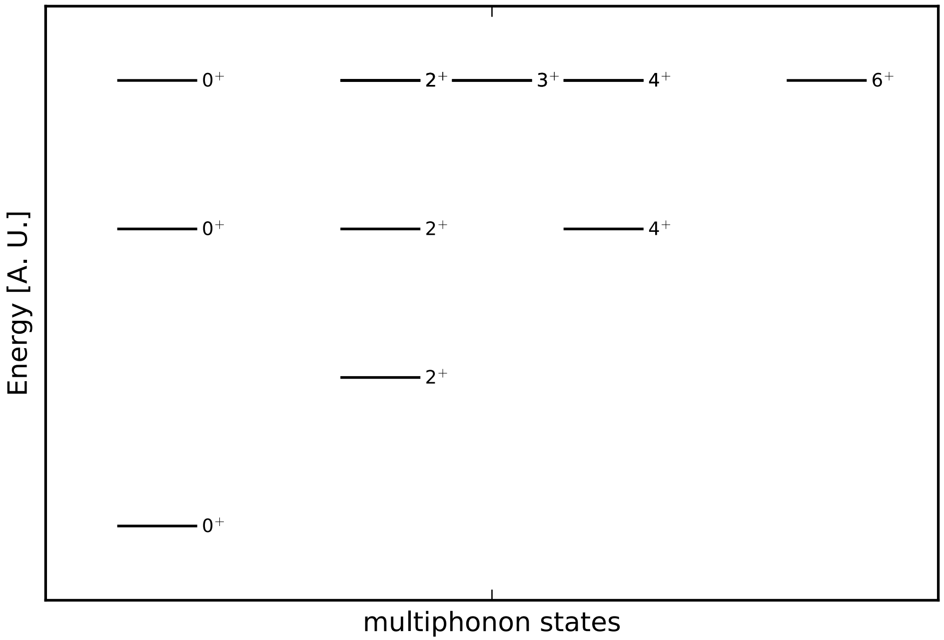
$$H_{\mathrm{LO}} \equiv \omega_1 \hat{N}$$

$$\hat{N} \equiv d^\dagger \cdot \tilde{d}$$

$$\omega_1 \sim \omega$$

The states are constructed as phonon excitations of the reference state

$$\left(d^{\dagger n}\right)_M^{(I)} |0\rangle$$



Coello Pérez, Papenbrock; Phys. Rev. C **92**, 064309 (2015)

$$H_{\text{LO}} \equiv \omega_1 \hat{N}$$

$$\hat{N} \equiv d^\dagger \cdot \tilde{d}$$

$$\omega_1 \sim \omega$$

Scales

low energies	breakdown
$H_{\text{LO}} \sim N\omega$	$H_{\text{LO}} \sim \Lambda$
$d \sim \sqrt{N}$	$d \sim \sqrt{\frac{\Lambda}{\omega}}$

ASSUMPTION: Corrections shift the energies by ω at breakdown $\Delta E \sim \omega$

Example: Scale of a term with four boson operators at breakdown

$$C_2 d^4 \sim \omega \quad \text{or} \quad C_2 \sim \left(\frac{\omega}{\Lambda}\right)^2 \omega$$

At low energies

$$C_2 d^4 \sim \left(\frac{N\omega}{\Lambda}\right)^2$$

NNLO Hamiltonian

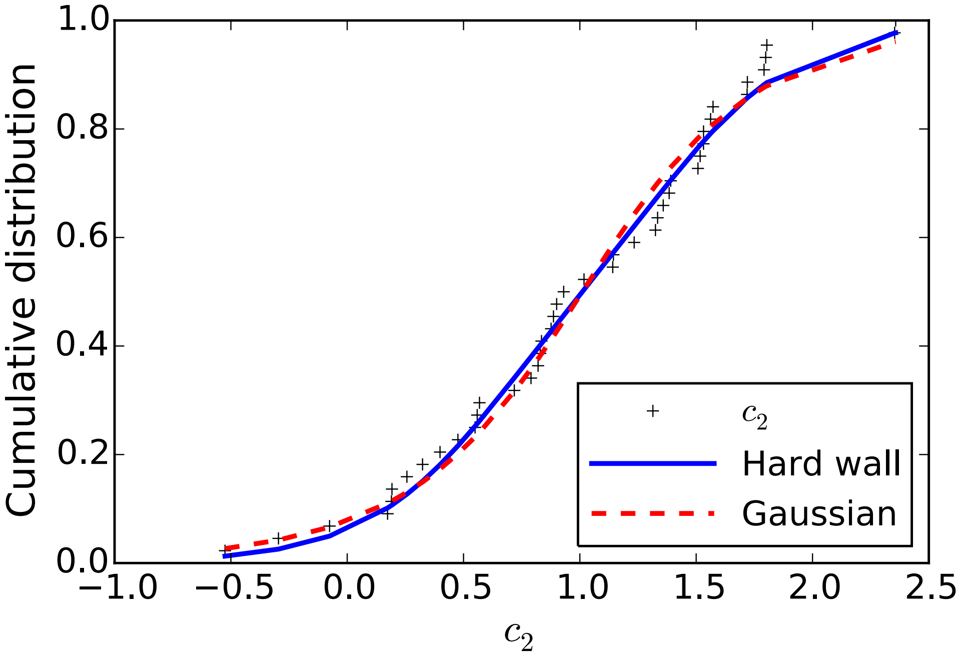
$$H_{\text{NNLO}} \equiv g_N \hat{N}^2 + g_v \hat{\Lambda}^2 + g_J \hat{J}^2$$

With

$$\hat{\Lambda}^2 \equiv -\left(d^\dagger \cdot d^\dagger\right)\left(\tilde{d} \cdot \tilde{d}\right) + \hat{N}^2 - 3\hat{N},$$

$$\hat{\mathbf{J}} = \sqrt{10}\left(d^\dagger \otimes \tilde{d}\right)^{(1)}$$

Testing the power counting



Observables (energy as an example)

$$E = \omega \sum_n^{\infty} c_n \varepsilon^n ,$$

$$\varepsilon \equiv \frac{N\omega}{\Lambda}$$

Expansion coefficients of order one
Assumption encoded into priors*

$$\mathrm{pr}^{(\mathrm{G})}(\tilde{c}_i|c) = \frac{1}{\sqrt{2\pi}sc} e^{-\frac{\tilde{c}_i^2}{2s^2c^2}}$$

$$\mathrm{pr}(c) = \frac{1}{\sqrt{2\pi}\sigma c} e^{-\frac{\log^2 c}{2\sigma^2}}$$

*Cacciari, Houdeau; Nucl. J. High Energy Phys. **09** (2011) 039
*Furnstahl, et al.; J. Phys. G **42**, 034028 (2015)

E2 operator

Most general positive-parity rank-two tensor

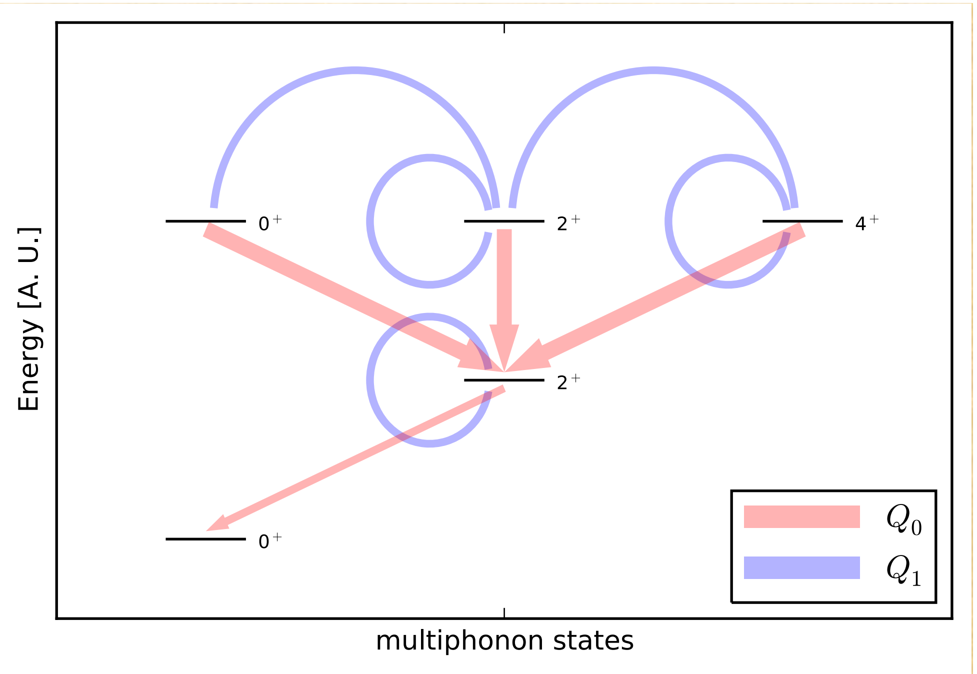
$$\hat{Q} = Q_0 \left(d^\dagger + \tilde{d}\right) + Q_1 \left(d^\dagger \otimes \tilde{d}\right)^{(2)}$$

ASSUMPTION: All terms scale similarly at breakdown

$$Q_1 \sim \sqrt{\frac{\omega}{\Lambda}} Q_0$$

Natural scaling

$$B \sim A \quad \Rightarrow \quad B \in \left[A\sqrt{\frac{\omega}{\Lambda}}, A\sqrt{\frac{\Lambda}{\omega}}\right]$$



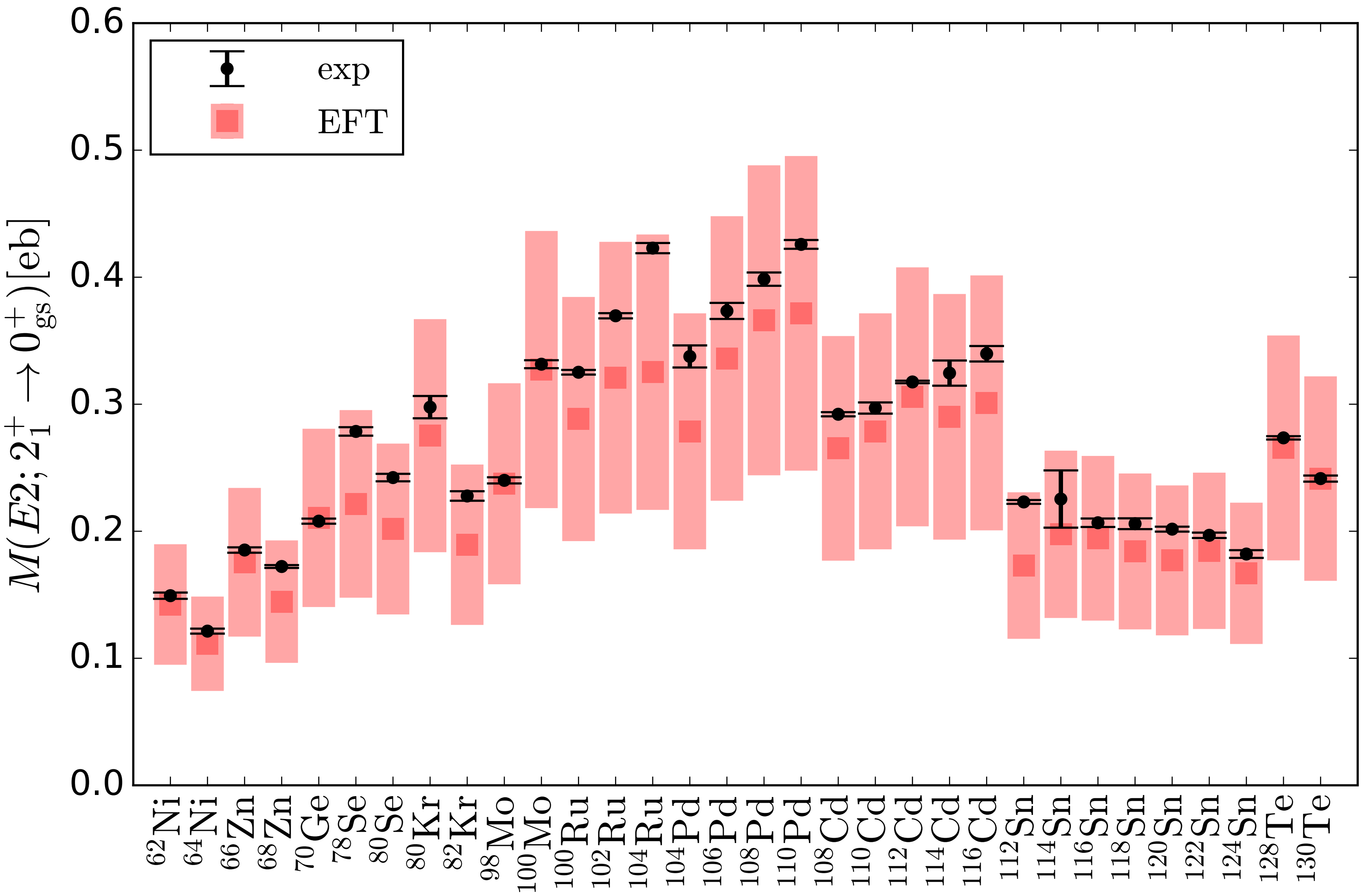
LO

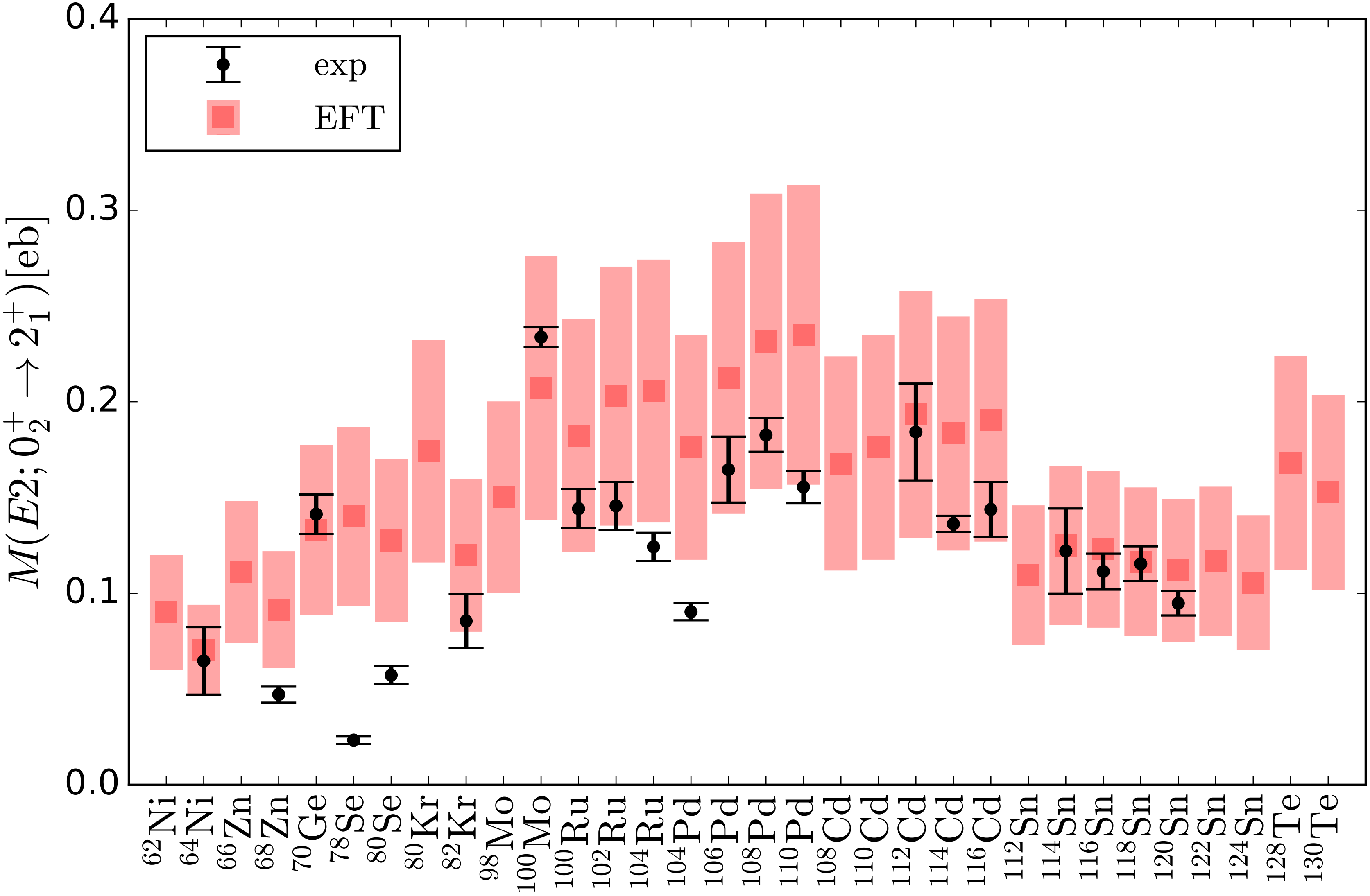
- Phonon-annihilating transitions

NLO

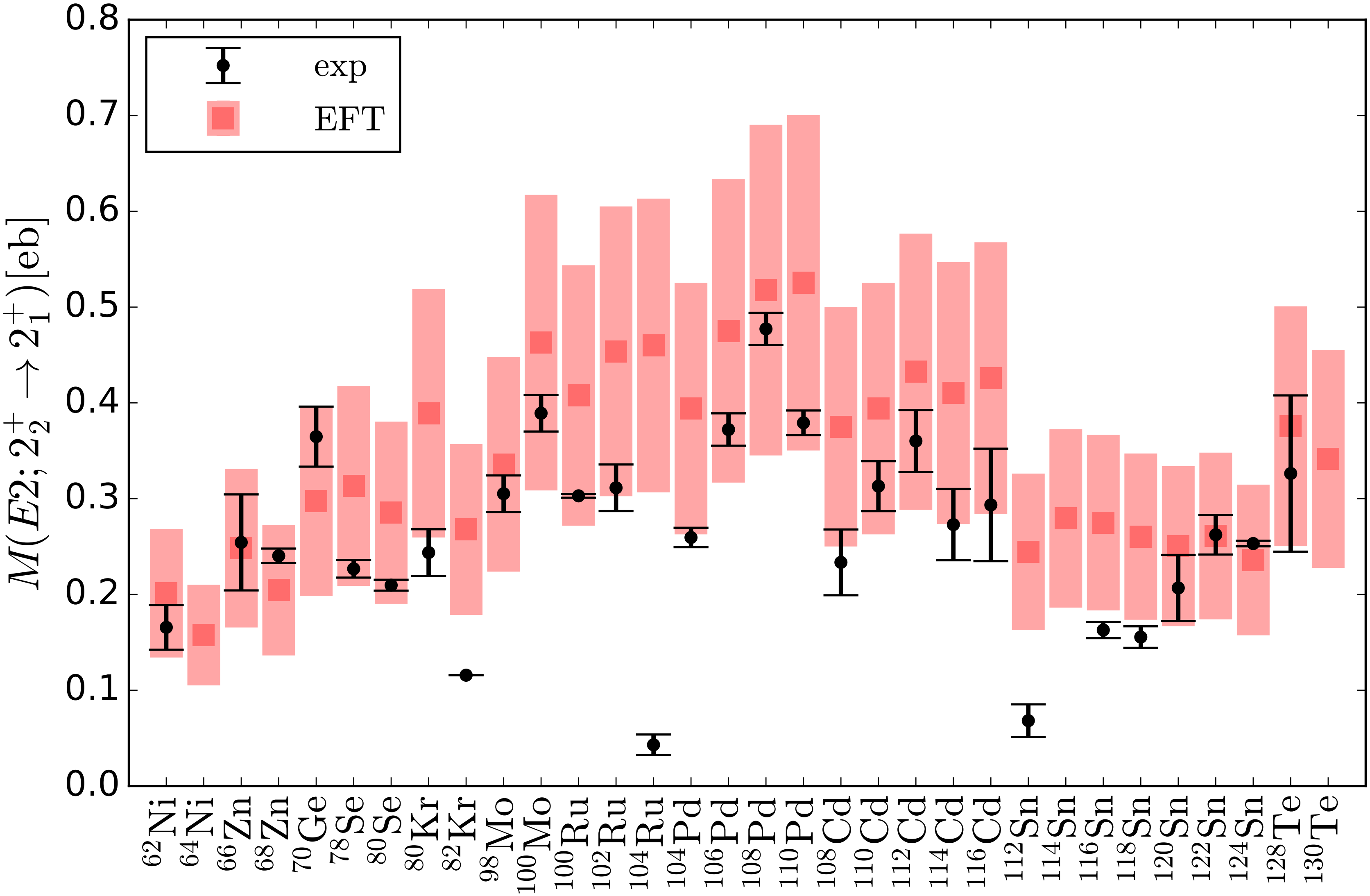
- Phonon-conserving transitions
- Static E2 moments

E2 transition matrix elements





0.4
0.3
0.2
0.1
0.0
$M(E2; 0_2^+ \to 2_1^+)$[eb]
exp
EFT
^{62}Ni
^{64}Ni
^{66}Zn
^{68}Zn
^{70}Ge
^{78}Se
^{80}Se
^{80}Kr
^{82}Kr
^{98}Mo
^{100}Mo
^{100}Ru
^{102}Ru
^{104}Ru
^{104}Pd
^{106}Pd
^{108}Pd
^{110}Pd
^{108}Cd
^{110}Cd
^{112}Cd
^{114}Cd
^{116}Cd
^{112}Sn
^{114}Sn
^{116}Sn
^{118}Sn
^{120}Sn
^{122}Sn
^{124}Sn
^{128}Te
^{130}Te



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$M(E2;2_2^+\to 2_1^+)$[eb]
exp
EFT
^{62}Ni
^{64}Ni
^{66}Zn
^{68}Zn
^{70}Ge
^{78}Se
^{80}Se
^{80}Kr
^{82}Kr
^{98}Mo
^{100}Mo
^{100}Ru
^{102}Ru
^{104}Ru
^{104}Pd
^{106}Pd
^{108}Pd
^{110}Pd
^{108}Cd
^{110}Cd
^{112}Cd
^{114}Cd
^{116}Cd
^{112}Sn
^{114}Sn
^{116}Sn
^{118}Sn
^{120}Sn
^{122}Sn
^{124}Sn
^{128}Te
^{130}Te

E2 transition matrix elements

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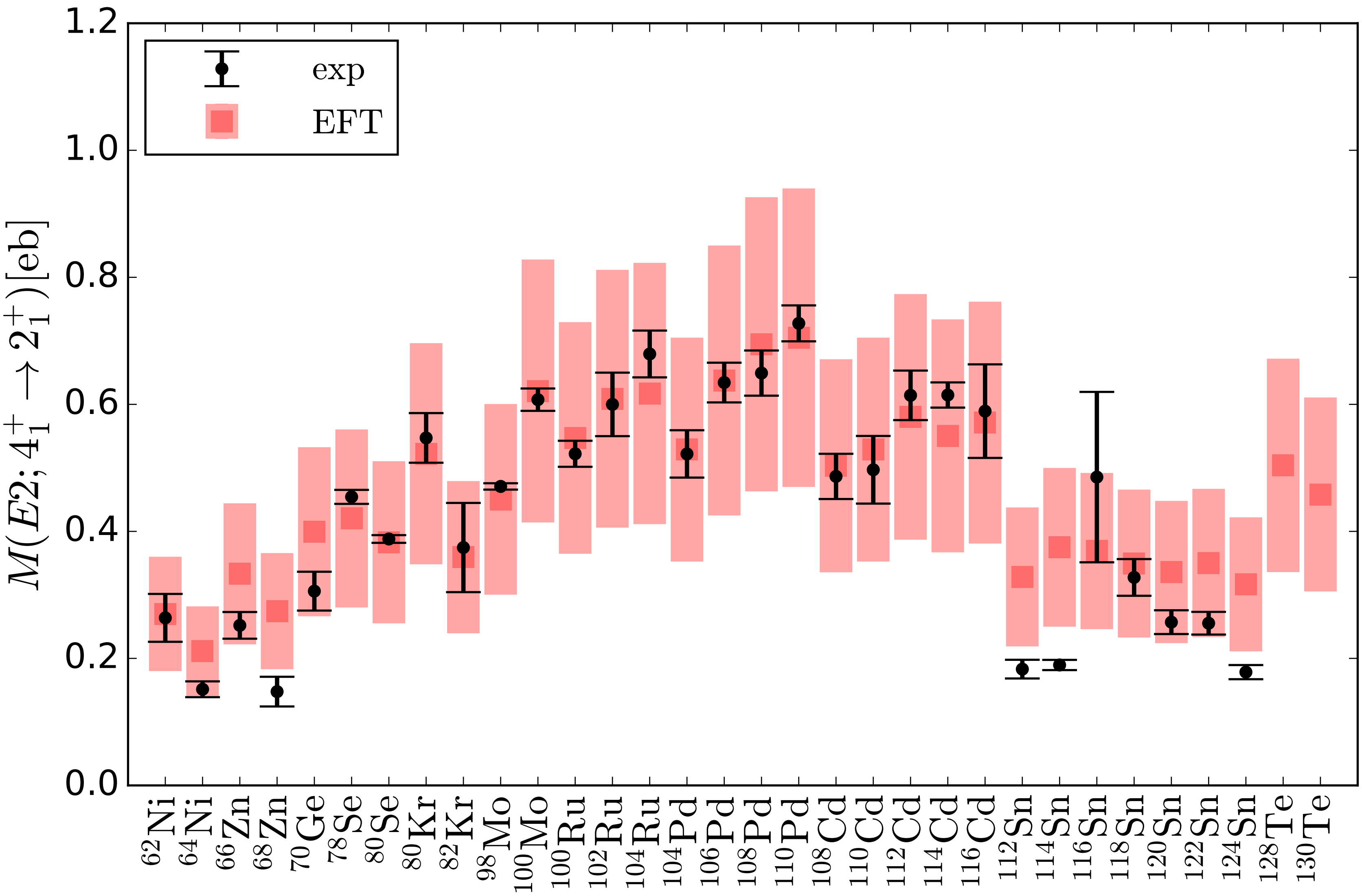
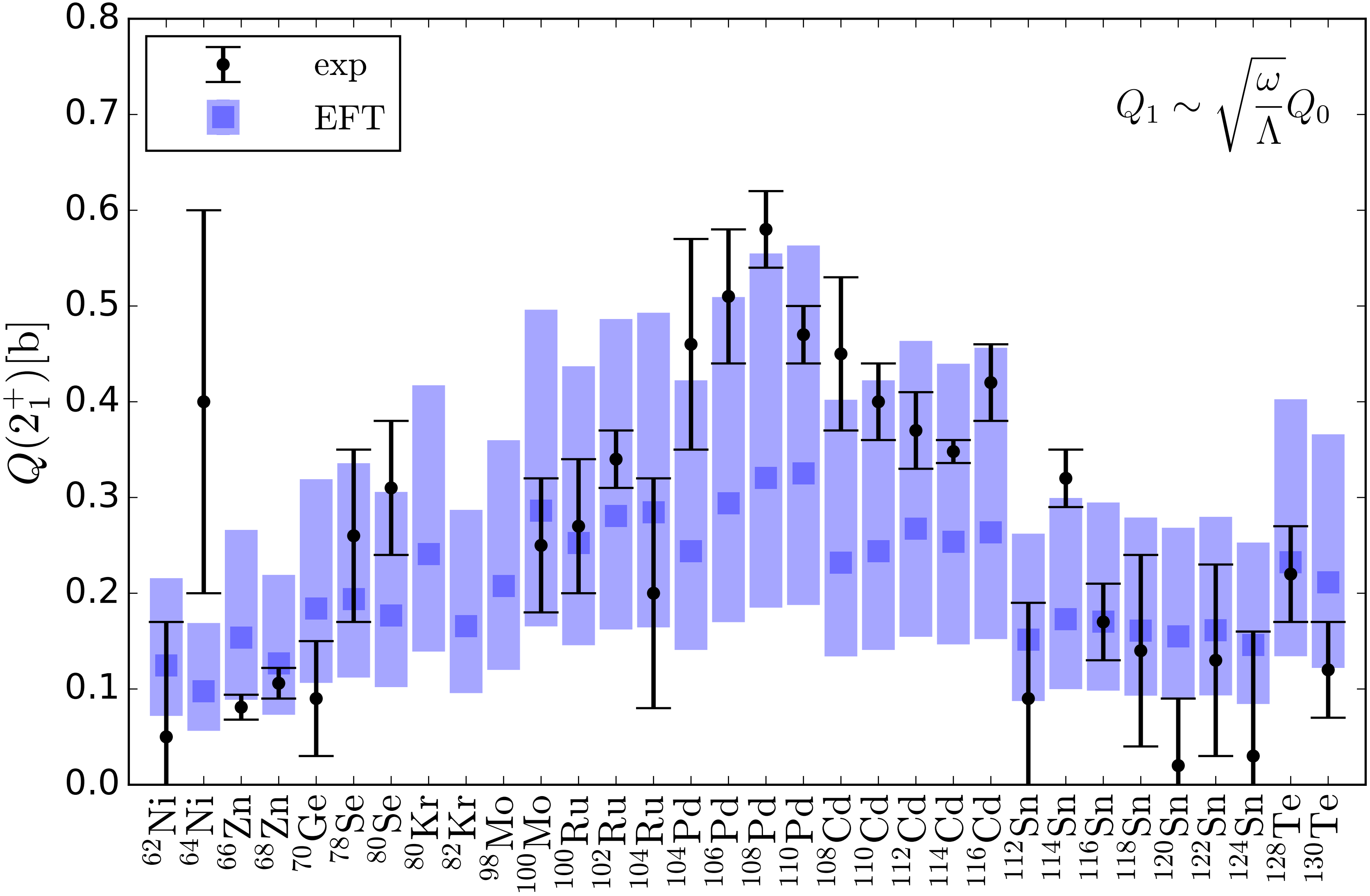
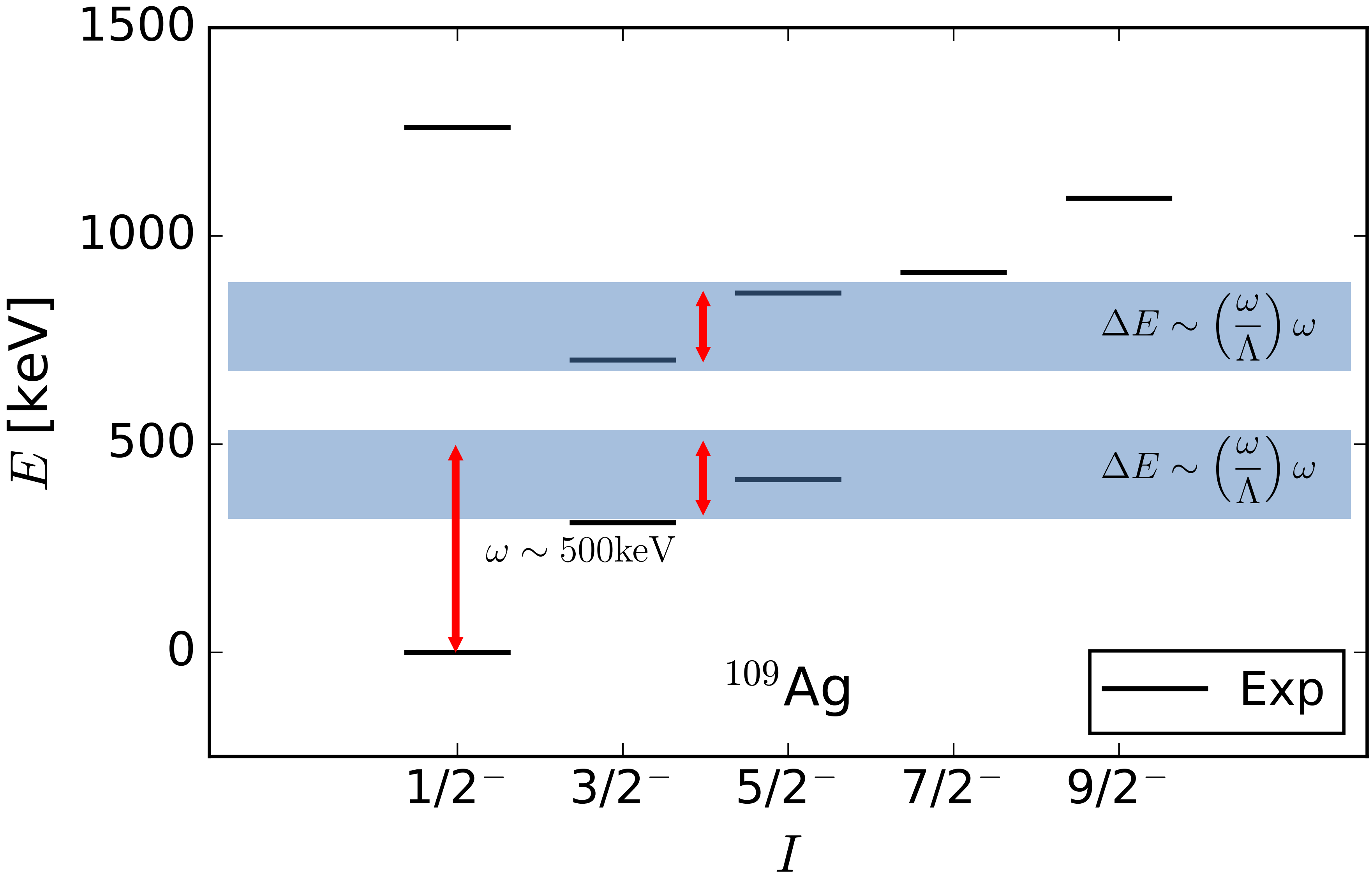


Static E2 moments




1500
1000
500
0
E [keV]
$\Delta E \sim \left(\frac{\omega}{\Lambda}\right)\omega$
$\Delta E \sim \left(\frac{\omega}{\Lambda}\right)\omega$
$\omega \sim 500\mathrm{keV}$
^{109}Ag
Exp
$1/2^-$
$3/2^-$
$5/2^-$
$7/2^-$
$9/2^-$
I

Degrees of freedom: fermion creation and annihilation operators for a fermion in a $j^\pi = {}^1/_2{}^-$ orbital

$$\{a_\mu, a_\nu^\dagger\} = \delta_{\mu\nu}$$

PROPOSAL: The matrix element of an operator with an *n*-fermion factor scales as

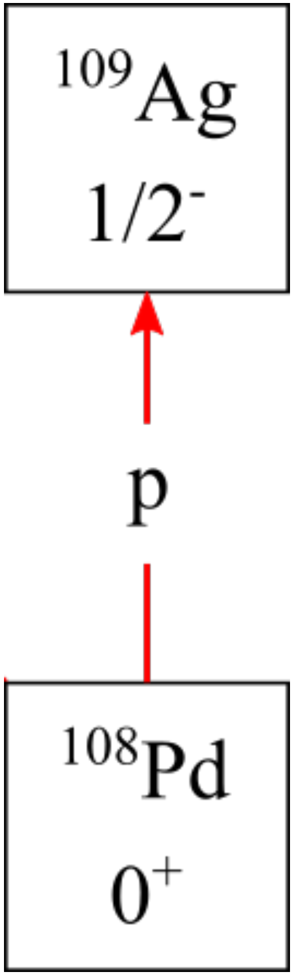
$$\langle \hat{O}_n \rangle \sim \langle \hat{O}_{n-1} \rangle \frac{\omega}{\Lambda}$$

NLO Hamiltonian

$$H_{\rm NLO} \equiv g_{Jj} \hat{\mathbf{J}} \cdot \hat{\mathbf{j}} + \omega_2 \hat{N} \hat{n}$$

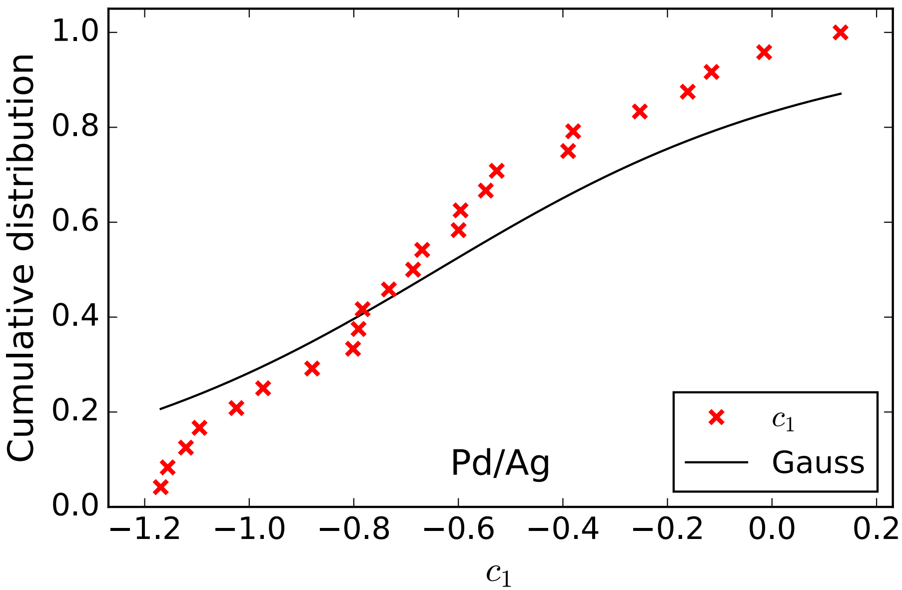
with

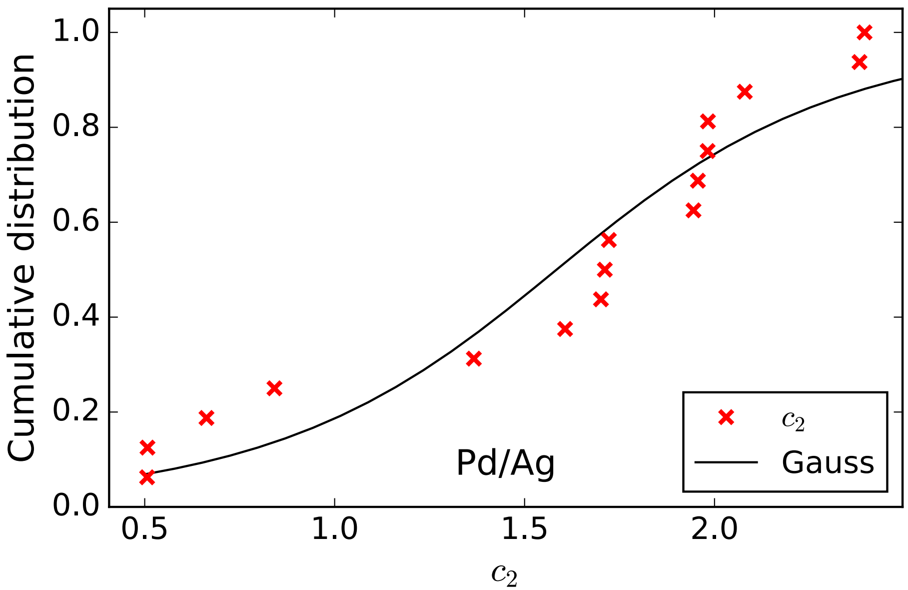
$$\hat{\mathbf{j}} = \frac{1}{\sqrt{2}} \left(a^\dagger \otimes \tilde{a}\right)^{(1)} \quad \text{and} \quad \hat{n} \equiv a^\dagger \cdot \tilde{a}$$



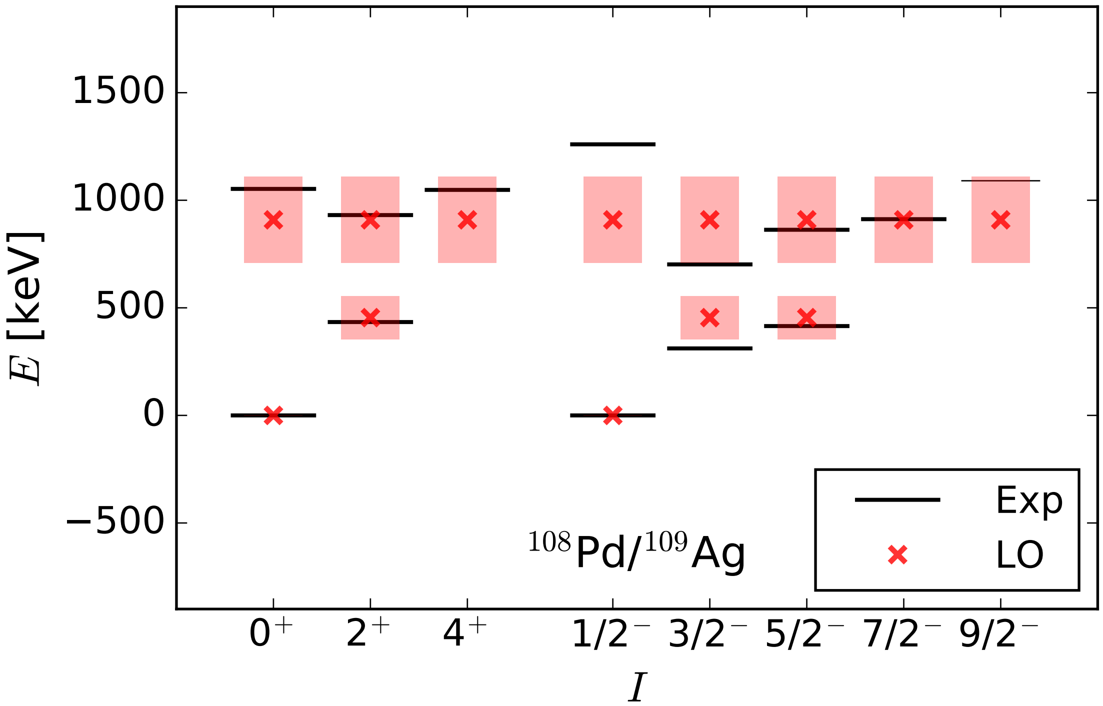
Coello Pérez, Papenbrock; Phys. Rev. C **94**, 054316 (2016)

Observables $E = \omega \sum_{n}^{\infty} c_n \varepsilon^n$, $\varepsilon \equiv \frac{N\omega}{\Lambda}$





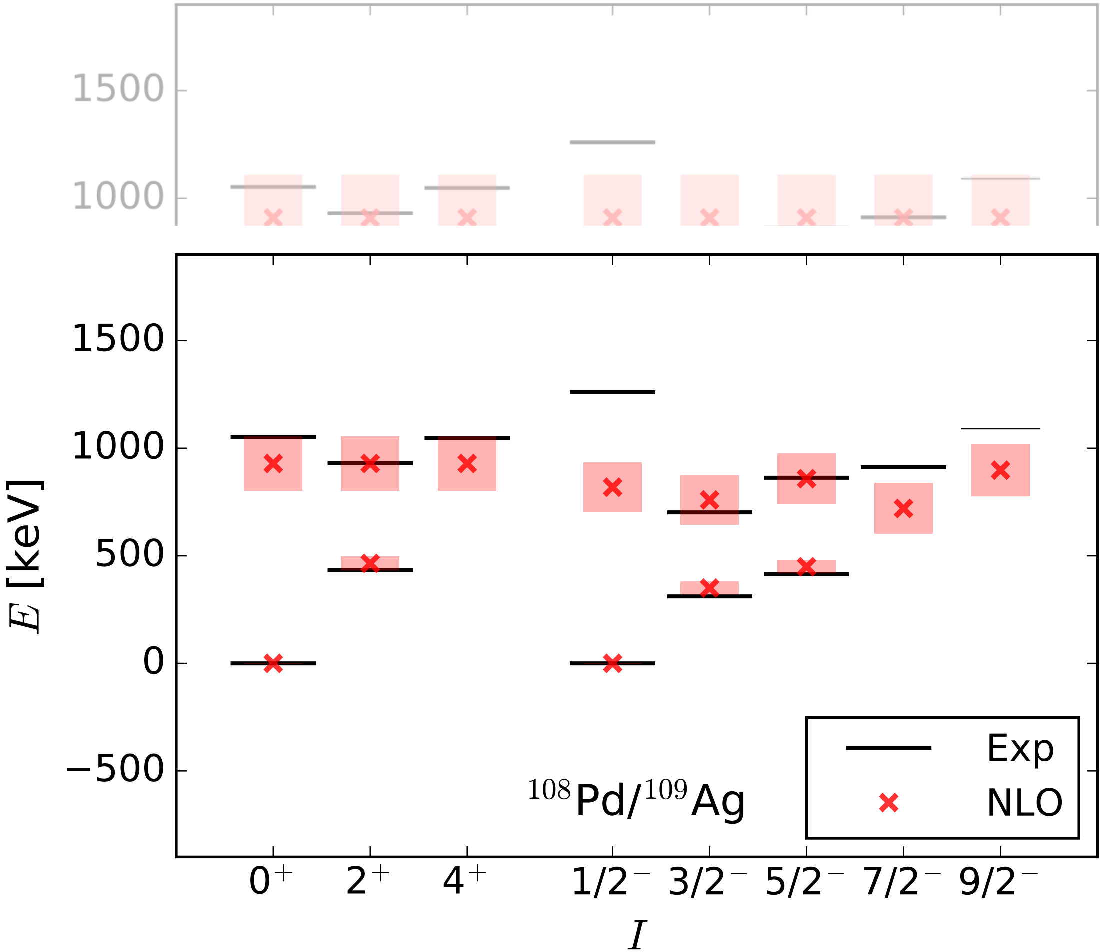
Order-by-order improvement



LO:

- One LEC
- Harmonic behavior

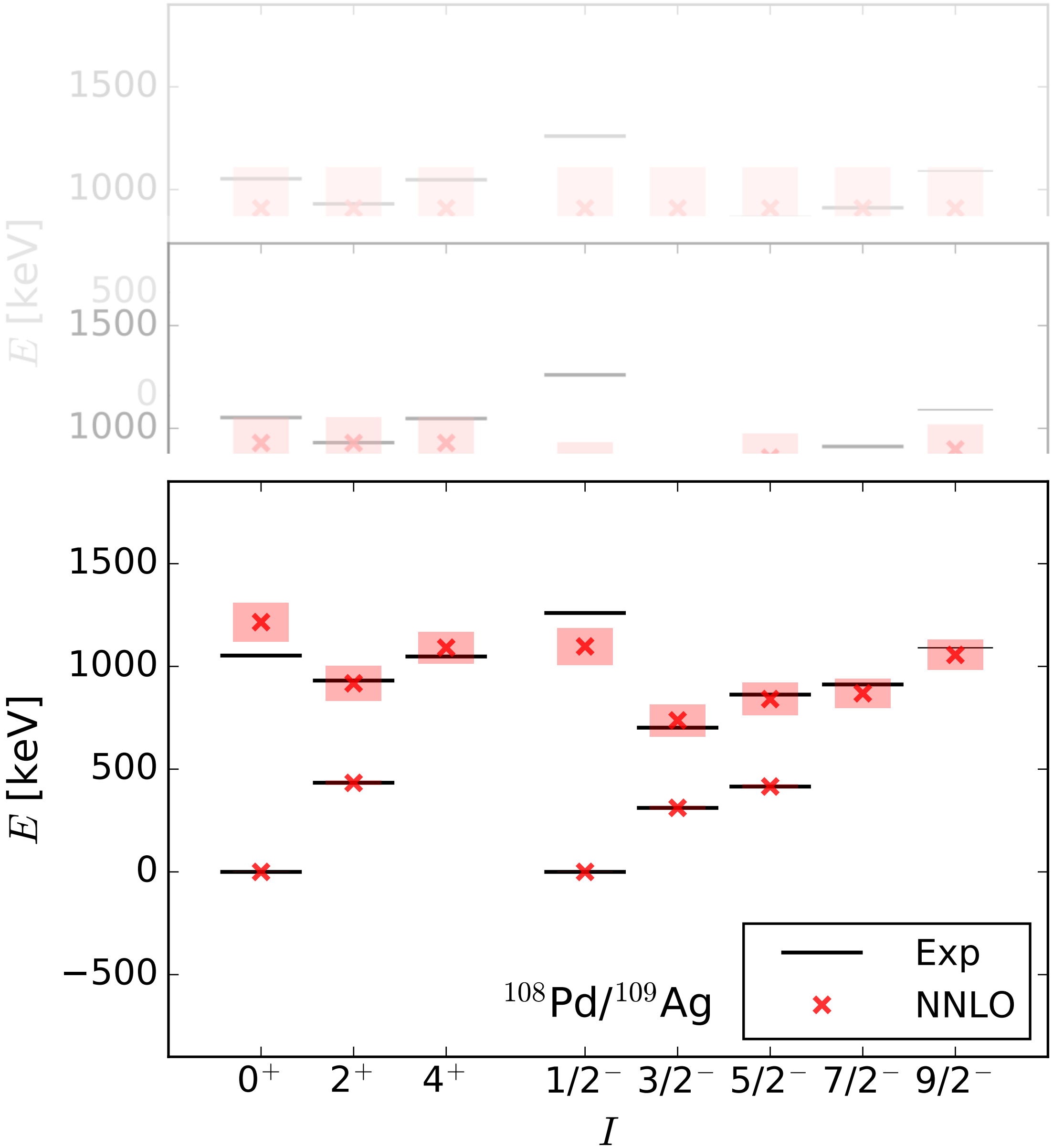
Order-by-order improvement



LO:
- One LEC
- Harmonic behavior

NLO:
- Two additional LECs
- Particle-core interactions

Order-by-order improvement



LO:
- One LEC
- Harmonic behavior

NLO:
- Two additional LECs
- Particle-core interactions

NNLO:
- Three additional LECs
- Anharmonic corrections

Accuracy and precision show an order-by-order increase of precision at the expense of reduced predictive power

E2 matrix elements

$$\hat{Q} = Q_0 \left(d^\dagger + \tilde{d} \right) + Q_1 \left(d^\dagger \otimes \tilde{d} \right)^{(2)}$$

Nucleus	$I_i^\pi \to I_f^\pi$	$M(E2)_{\mathrm{exp}}$	$M(E2)_{\mathrm{EFT}}$
^{102}Ru	$2_1^+ \to 0_1^+$	0.370(2)	0.306(102)
	$0_2^+ \to 2_1^+$	0.146(12)	0.194(65)
	$2_2^+ \to 2_1^+$	0.311(24)	0.433(144)
	$4_1^+ \to 2_1^+$	0.600(50)	0.581(194)
^{103}Rh	$\frac{3}{2}^-_1 \to \frac{1}{2}^-_1$	0.297(16)	0.274(91)
	$\frac{5}{2}^-_1 \to \frac{1}{2}^-_1$	0.402(14)	0.336(112)
	$\frac{1}{2}^-_2 \to \frac{3}{2}^-_1$		0.173(58)
	$\frac{1}{2}^-_2 \to \frac{5}{2}^-_1$	0.244(23)	0.212(71)
	$\frac{3}{2}^-_2 \to \frac{3}{2}^-_1$		0.324(108)
	$\frac{3}{2}^-_2 \to \frac{5}{2}^-_1$		0.212(71)
	$\frac{5}{2}^-_2 \to \frac{3}{2}^-_1$	0.100(7)	212(71)
	$\frac{5}{2}^-_2 \to \frac{5}{2}^-_1$	0.121(9)	0.424(141)
	$\frac{7}{2}^-_1 \to \frac{3}{2}^-_1$	0.408(66)	0.520(173)
	$\frac{7}{2}^-_1 \to \frac{5}{2}^-_1$		0.173(58)
	$\frac{9}{2}^-_1 \to \frac{5}{2}^-_1$	0.531(40)	0.613(204)

Nucleus	$I_i^\pi \to I_f^\pi$	$M(E2)_{\mathrm{exp}}$	$M(E2)_{\mathrm{EFT}}$
^{108}Pd	$2_1^+ \to 0_{\mathrm{gs}}^+$	0.398(5)	0.341(114)
	$0_2^+ \to 2_1^+$	0.183(9)	0.216(72)
	$2_2^+ \to 2_1^+$	0.477(17)	0.482(161)
	$4_1^+ \to 2_1^+$	0.649(36)	0.647(216)
^{109}Ag	$\frac{3}{2}^-_1 \to \frac{1}{2}^-_{\mathrm{gs}}$	0.322(161)	0.305(102)
	$\frac{5}{2}^-_1 \to \frac{1}{2}^-_1$	0.397(8)	0.373(124)
	$\frac{1}{2}^-_2 \to \frac{3}{2}^-_1$		0.193(64)
	$\frac{1}{2}^-_2 \to \frac{5}{2}^-_1$		0.236(79)
	$\frac{3}{2}^-_2 \to \frac{3}{2}^-_1$	0.356(87)	0.361(120)
	$\frac{3}{2}^-_2 \to \frac{5}{2}^-_1$		0.236(79)
	$\frac{5}{2}^-_2 \to \frac{3}{2}^-_1$	0.176(44)	0.236(79)
	$\frac{5}{2}^-_2 \to \frac{5}{2}^-_1$	0.197(69)	0.472(157)
	$\frac{7}{2}^-_1 \to \frac{3}{2}^-_1$		0.579(193)
	$\frac{7}{2}^-_1 \to \frac{5}{2}^-_1$		0.193(64)
	$\frac{9}{2}^-_1 \to \frac{5}{2}^-_1$	0.664(54)	0.682(227)

Data: Nuclear Data Sheets

M1 operator

Most general operator of rank one

$$\hat{\mu} = \mu_d \hat{\mathbf{J}} + \mu_a \hat{\mathbf{j}} + \left[\left(d^\dagger + \tilde{d} \right) \otimes \left(\mu_{d1} \hat{\mathbf{J}} + \mu_{a1} \hat{\mathbf{j}} \right) \right]^{(1)}$$

LO term:

- Two LECs
- Phonon-conserving transition
- Static M1 moments

NLO term:

- Two LECs
- Phonon-annihilating transition

Static M1 static moments and M1 transition matrix elements

Nucleus	I_i^π	μ_{exp}	μ_{EFT}
^{102}Ru	2_1^+	0.85(3)	1.02(34)
	2_2^+		1.02(34)
	4_1^+		2.04(68)
^{103}Rh	$\frac{1}{2}_1$	−0.09	−0.08(3)
	$\frac{3}{2}_1$	0.77(7)	0.97(32)
	$\frac{5}{2}_1$	1.08(4)	0.93(31)
	$\frac{7}{2}_1$	2.00(60)	2.04(68)
	$\frac{9}{2}_1$	2.80(50)	1.95(65)
^{106}Pd	2_1^+	0.79(2)	0.91(30)
	2_2^+	0.71(10)	0.91(30)
	4_1^+	1.80(40)	1.81(60)
^{107}Ag	$\frac{1}{2}_1$	−0.11	−0.11(4)
	$\frac{3}{2}_1$	0.98(9)	0.88(29)
	$\frac{5}{2}_1$	1.02(9)	0.80(27)
	$\frac{7}{2}_1$		1.85(62)
	$\frac{9}{2}_1$		1.71(57)
^{108}Pd	2_1^+	0.71(2)	0.93(31)
	2_2^+		0.93(31)
	4_1^+		1.86(62)
^{109}Ag	$\frac{1}{2}_1$	−0.13	−0.13(4)
	$\frac{3}{2}_1$	1.10(10)	0.91(30)
	$\frac{5}{2}_1$	0.85(8)	0.80(26)
	$\frac{7}{2}_1$		1.91(64)
	$\frac{9}{2}_1$		1.72(57)

$$\hat{\mu} = \mu_d \hat{\mathbf{J}} + \mu_a \hat{\mathbf{j}} + \left[\left(d^\dagger + \tilde{d} \right) \otimes \left(\mu_{d1} \hat{\mathbf{J}} + \mu_{a1} \hat{\mathbf{j}} \right) \right]^{(1)}$$

LECs fitted to static M1 moments

Nucleus	$I_i^\pi \rightarrow I_f^\pi$	$M(M1)_{\mathrm{exp}}$	$M(M1)_{\mathrm{EFT}}$
^{103}Rh	$\frac{5}{2}^-_1 \rightarrow \frac{3}{2}^-_1$		0.512(171)
	$\frac{5}{2}^-_2 \rightarrow \frac{3}{2}^-_2$		0.512(171)
	$\frac{9}{2}^-_1 \rightarrow \frac{7}{2}^-_1$		0.697(232)
^{107}Ag	$\frac{5}{2}^-_1 \rightarrow \frac{3}{2}^-_1$	0.595(36)	0.506(169)
	$\frac{5}{2}^-_2 \rightarrow \frac{3}{2}^-_2$		0.506(169)
	$\frac{9}{2}^-_1 \rightarrow \frac{7}{2}^-_1$		0.689(230)
^{109}Ag	$\frac{5}{2}^-_1 \rightarrow \frac{3}{2}^-_1$	0.680(55)	0.551(184)
	$\frac{5}{2}^-_2 \rightarrow \frac{3}{2}^-_2$		0.551(184)
	$\frac{9}{2}^-_1 \rightarrow \frac{7}{2}^-_1$		0.750(250)

Data: Nuclear Data Sheets

M1 transition matrix elements

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$$\hat{\mu} = \mu_d \hat{\mathbf{J}} + \mu_a \hat{\mathbf{j}} + \left[\left(d^\dagger + \tilde{d} \right) \otimes \left(\mu_{d1} \hat{\mathbf{J}} + \mu_{a1} \hat{\mathbf{j}} \right) \right]^{(1)}$$

Nucleus	$I_i^\pi \to I_f^\pi$	$M(M1)_{\mathrm{exp}}$	$M(M1)_{\mathrm{EFT}}$
^{103}Rh	$\frac{3}{2}^-_1 \to \frac{1}{2}^-_1$	0.568(24)	0.566(189)
	$\frac{1}{2}^-_2 \to \frac{3}{2}^-_1$		0.358(119)
	$\frac{3}{2}^-_2 \to \frac{3}{2}^-_1$		0.624(208)
	$\frac{3}{2}^-_2 \to \frac{5}{2}^-_1$		0.291(97)
	$\frac{5}{2}^-_2 \to \frac{3}{2}^-_1$	0.250(18)	0.291(97)
	$\frac{5}{2}^-_2 \to \frac{5}{2}^-_1$	0.299(22)	0.289(96)
	$\frac{7}{2}^-_1 \to \frac{5}{2}^-_1$		1.074(358)
^{109}Ag	$\frac{3}{2}^-_1 \to \frac{1}{2}^-_1$	0.560(36)	0.612(204)
	$\frac{1}{2}^-_2 \to \frac{3}{2}^-_1$		0.387(129)
	$\frac{3}{2}^-_2 \to \frac{3}{2}^-_1$	0.655(143)	0.506(169)
	$\frac{3}{2}^-_2 \to \frac{5}{2}^-_1$		0.371(124)
	$\frac{5}{2}^-_2 \to \frac{3}{2}^-_1$	0.401(89)	0.371(124)
	$\frac{5}{2}^-_2 \to \frac{5}{2}^-_1$	0.669(134)	0.523(174)
	$\frac{7}{2}^-_1 \to \frac{5}{2}^-_1$		1.162(387)

Data: Nuclear Data Sheets

Low-lying positive-parity odd-odd states are constructed as

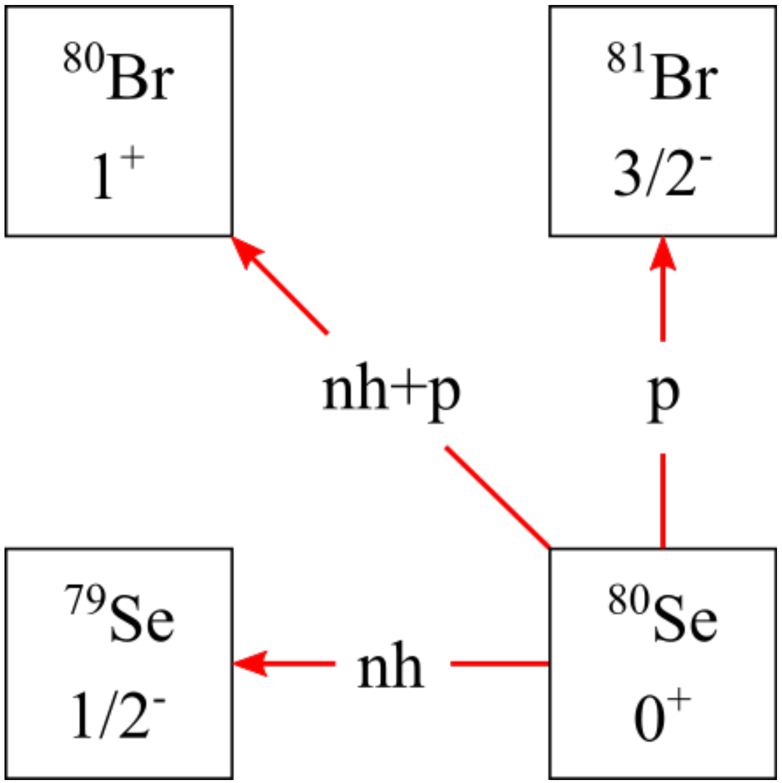
$$|IM; j_p; j_n\rangle = \sum_{\mu\nu} C^{IM}_{j_n\mu j_p\nu} n^\dagger_\mu p^\dagger_\nu |0\rangle$$

where

$$|j_n - j_p| \leq I \leq j_n + j_p$$

and

$$\pi_n \pi_p = 1$$



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Most general rank-one operator coupling odd-odd and even-even states

$$
\begin{aligned}
\hat{O}_\beta =& C_\beta \, (\tilde{p} \otimes \tilde{n})^{(1)} \\
&+ \sum_{\ell} C_{\beta\ell} \left[\left(d^\dagger + \tilde{d} \right) \otimes (\tilde{p} \otimes \tilde{n})^{(\ell)} \right]^{(1)} \\
&+ \sum_{L\ell} C_{\beta L\ell} \left[\left(d^\dagger \otimes d^\dagger + \tilde{d} \otimes \tilde{d} \right)^{(L)} \otimes (\tilde{p} \otimes \tilde{n})^{(\ell)} \right]^{(1)}
\end{aligned}
$$

LO term:

- Couples states with $\Delta\mathcal{N} = 0$

NLO term:

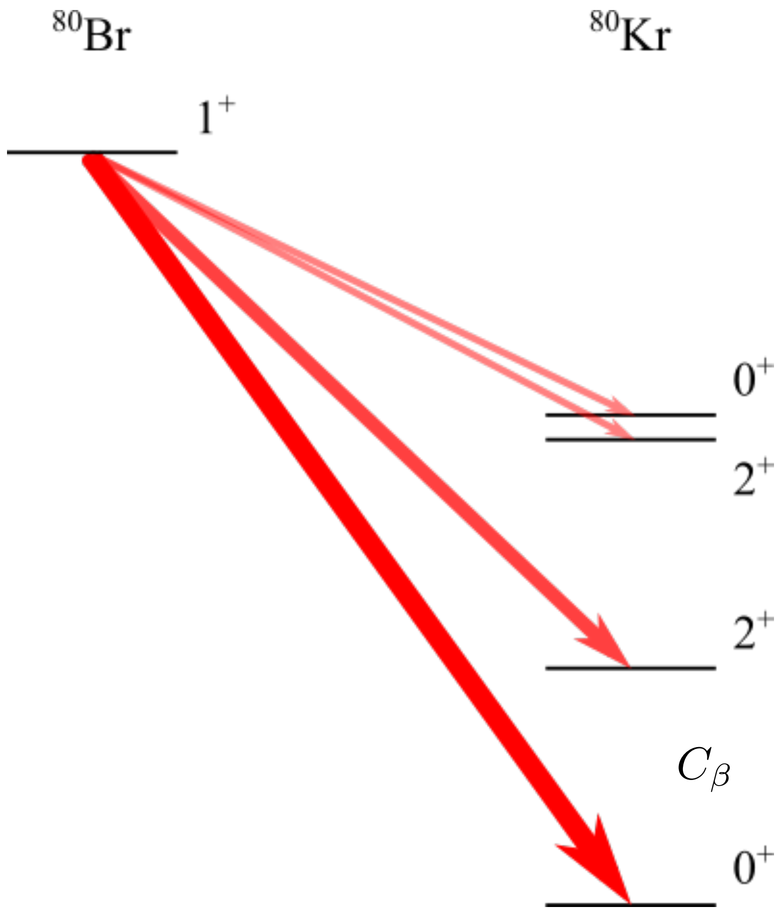
- Couples states with $\Delta\mathcal{N} = 1$

NNLO term:

- Couples states with $\Delta\mathcal{N} = 2$

From the power counting

$$\frac{C_{\beta\ell}}{C_\beta} \overset{\text{EFT}}{\sim} 0.58(^{+42}_{-25}) \quad \text{and} \quad \frac{C_{\beta L\ell}}{C_\beta} \overset{\text{EFT}}{\sim} 0.33(^{+25}_{-14})$$



Uncertainty estimate for single-β decays to the ground state

Corrections to odd-odd Hamiltonian

$$\sqrt{\omega/\Lambda}$$

Corrections to the effective GT operator

$$\omega/\Lambda$$

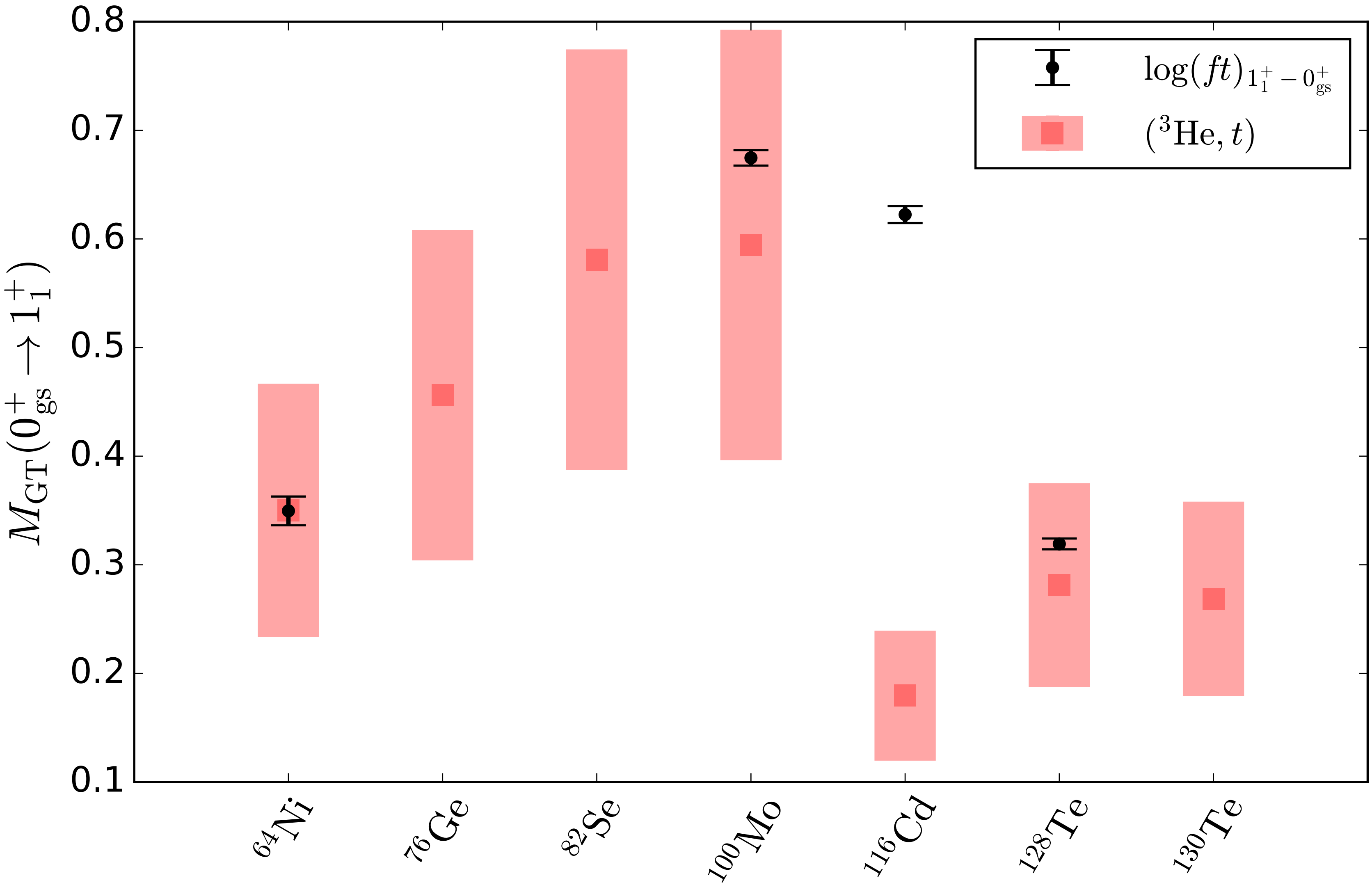
Uncertainty estimate

$$\Delta\langle 0||\hat{O}_\beta||I;j_p;j_n\rangle \overset{\text{EFT}}{\sim} \langle 0||\hat{O}_\beta||I;j_p;j_n\rangle \frac{\omega}{\Lambda}$$

or

$$\Delta \log(ft)_{if} \overset{\text{EFT}}{\sim} \frac{2}{\ln 10}\frac{\omega}{\Lambda}$$

LEC from charge-exchange reaction experiments



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Matrix elements for single-β decays

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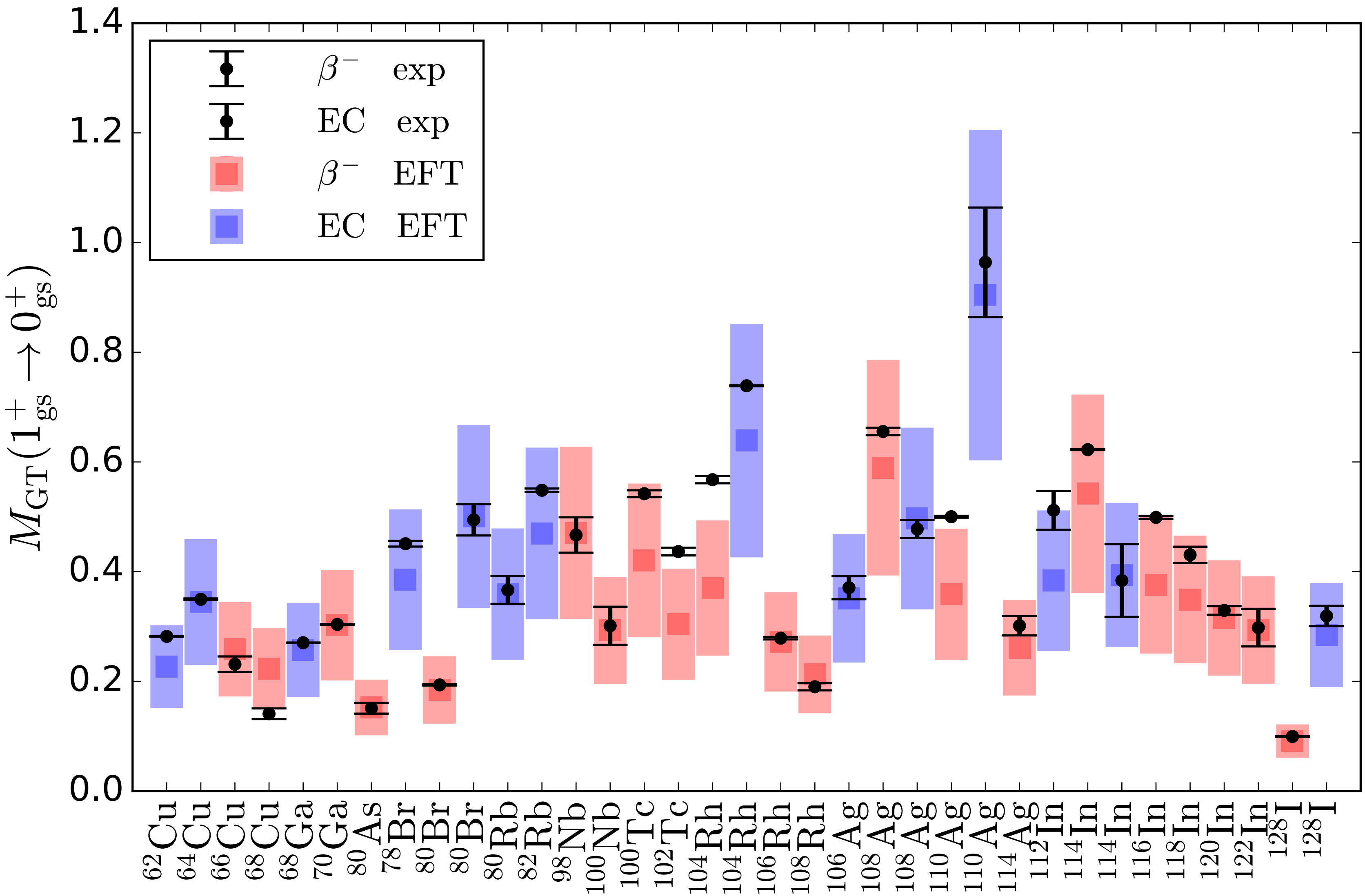

Coello Pérez, Menéndez, Schwenk; in preparation

Data: Nuclear Data Sheets

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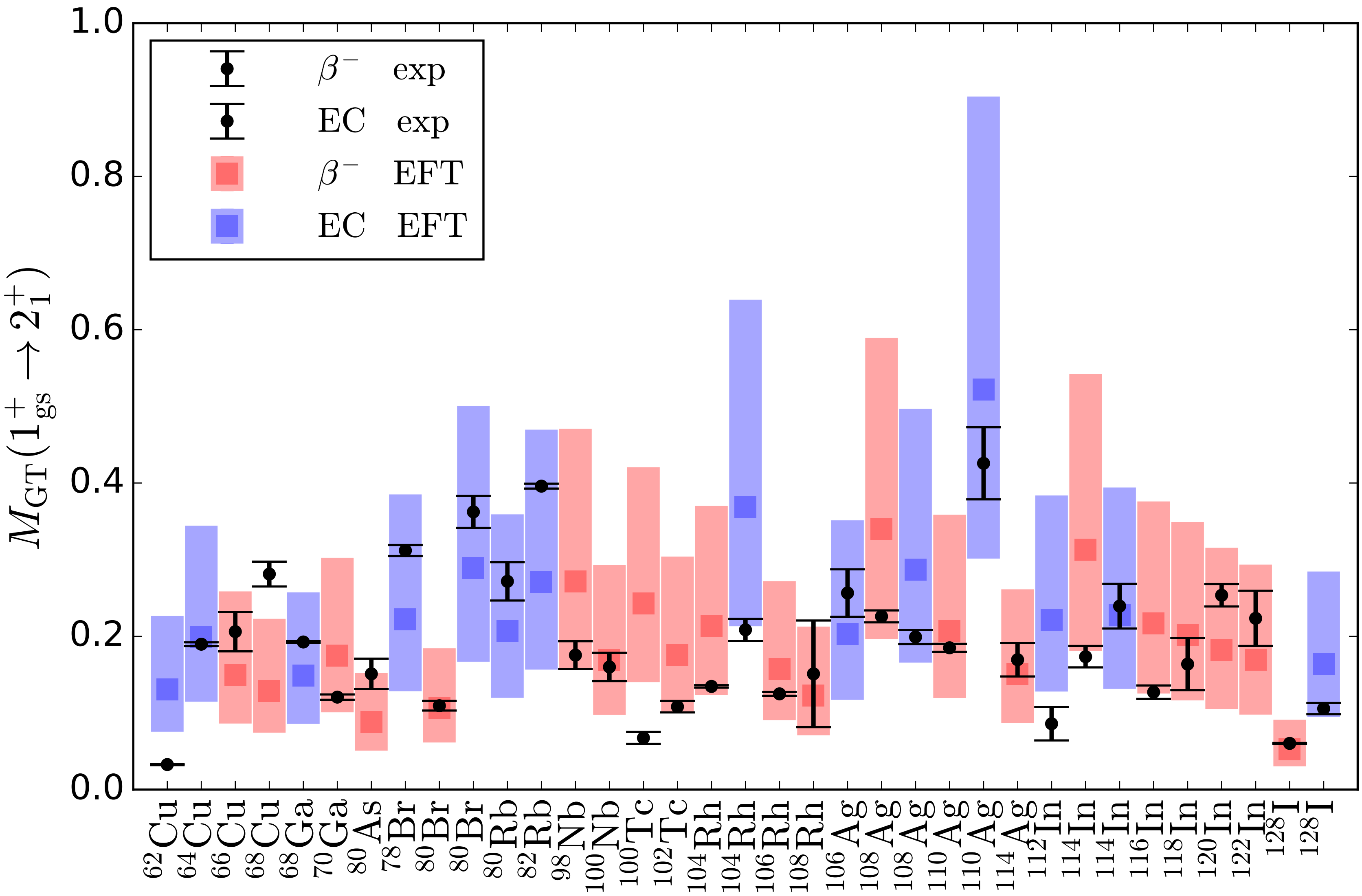

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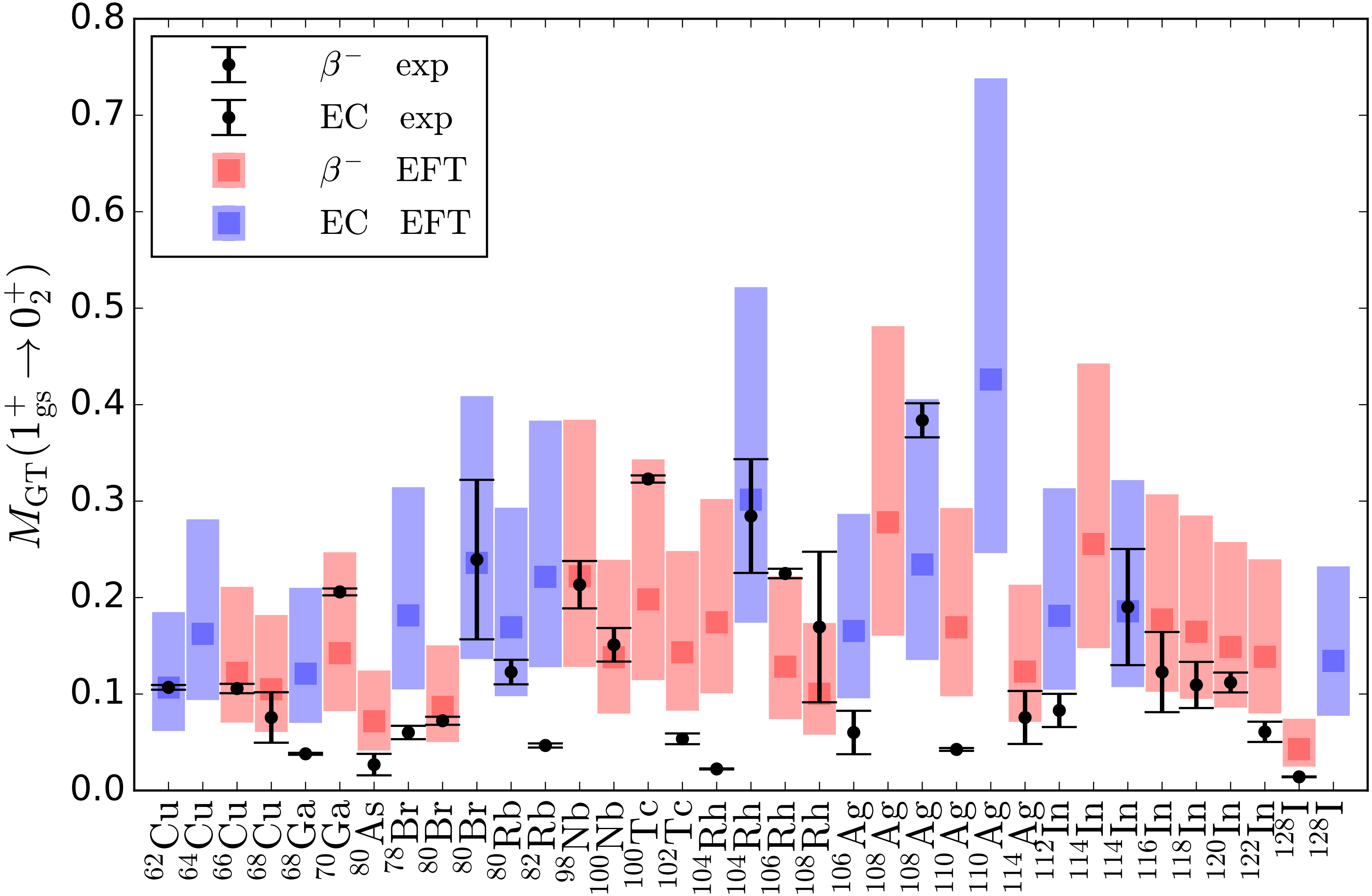
Data: Nuclear Data Sheets



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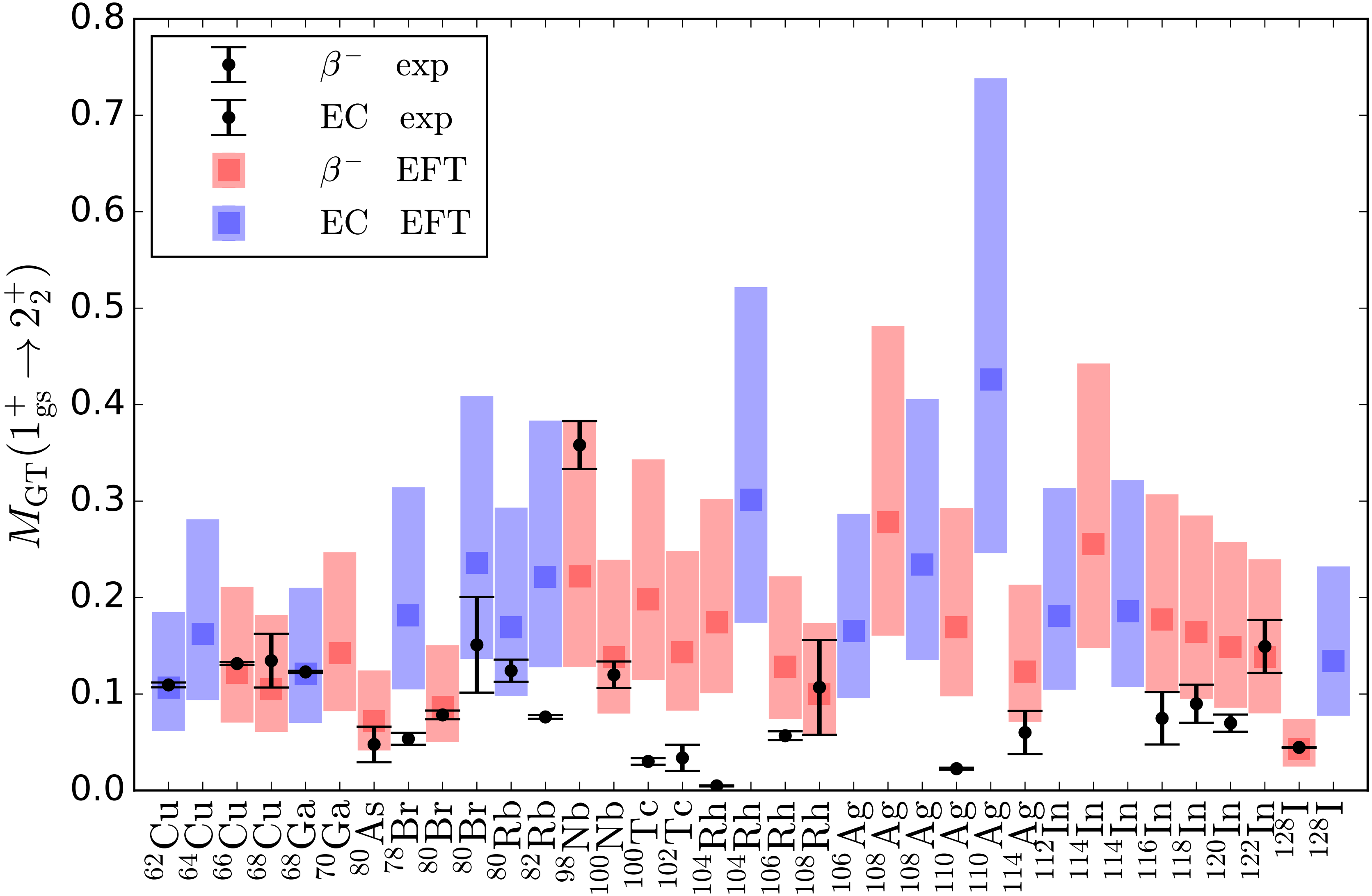
Data: Nuclear Data Sheets



Coello Pérez, Menéndez, Schwenk; in preparation

Data: Nuclear Data Sheets

GT matrix elements for $2\nu\beta\beta$ decay

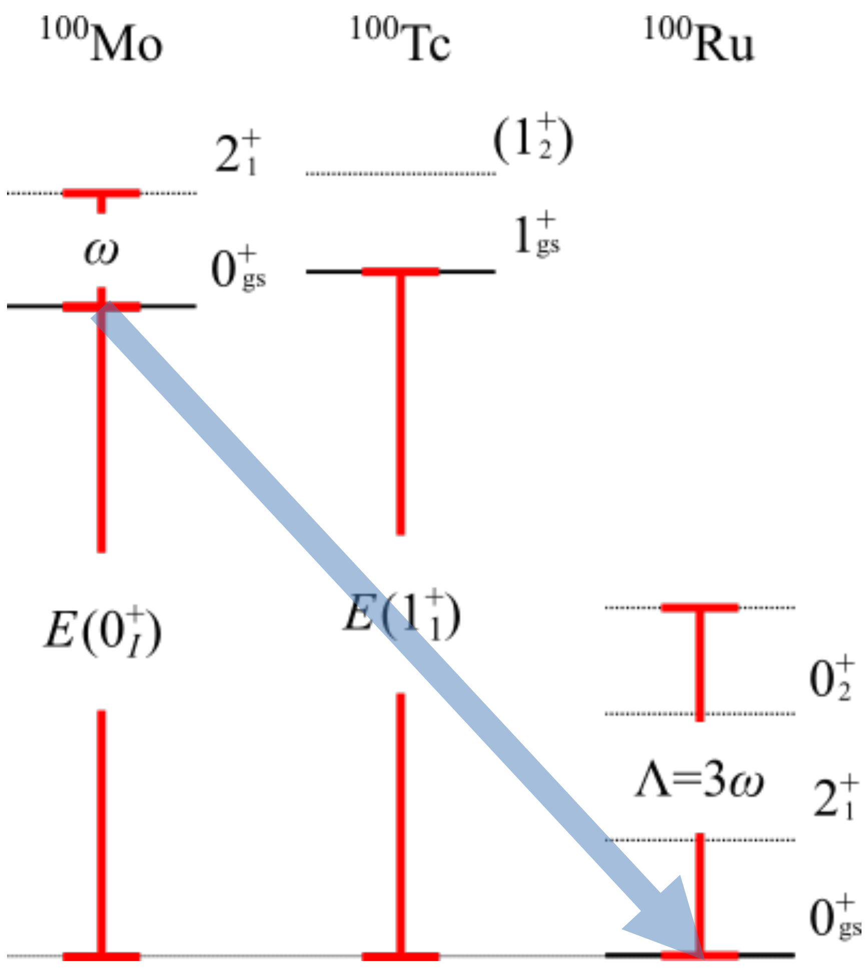
$$M_{\rm GT}^{2\nu} = \sum_n \frac{\langle f || \sum_a \boldsymbol{\sigma}_a \tau_a^+ || 1_n^+ \rangle \langle 1_n^+ || \sum_b \boldsymbol{\sigma}_b \tau_b^+ || i \rangle}{D_{nf}/m_e}$$

with

$$D_{nf} = E_n - \frac{E_i - E_f}{2}$$

SSD approximation

$$M_{\rm GT}^{2\nu}(i \to f) \approx \frac{M_{\rm GT}(1_1^+ \to 0_f^+) M_{\rm GT}(0_i^+ \to 1_1^+)}{D_{1f}/m_e c^2}$$



ASSUMPTION: Energies and matrix elements of 1^+ states scale as

$$E(1^+_{n+1}) \overset{\text{EFT}}{\sim} E(1^+_1) + n\omega \quad \text{and} \quad M_{\text{GT}}\left(0^+_{\text{gs}} \to 1^+_{n+1}\right) \overset{\text{EFT}}{\sim} \left(\frac{\omega}{\Lambda}\right)^{n/2} M_{\text{GT}}\left(0^+_{\text{gs}} \to 1^+_1\right)$$

Omitted contribution

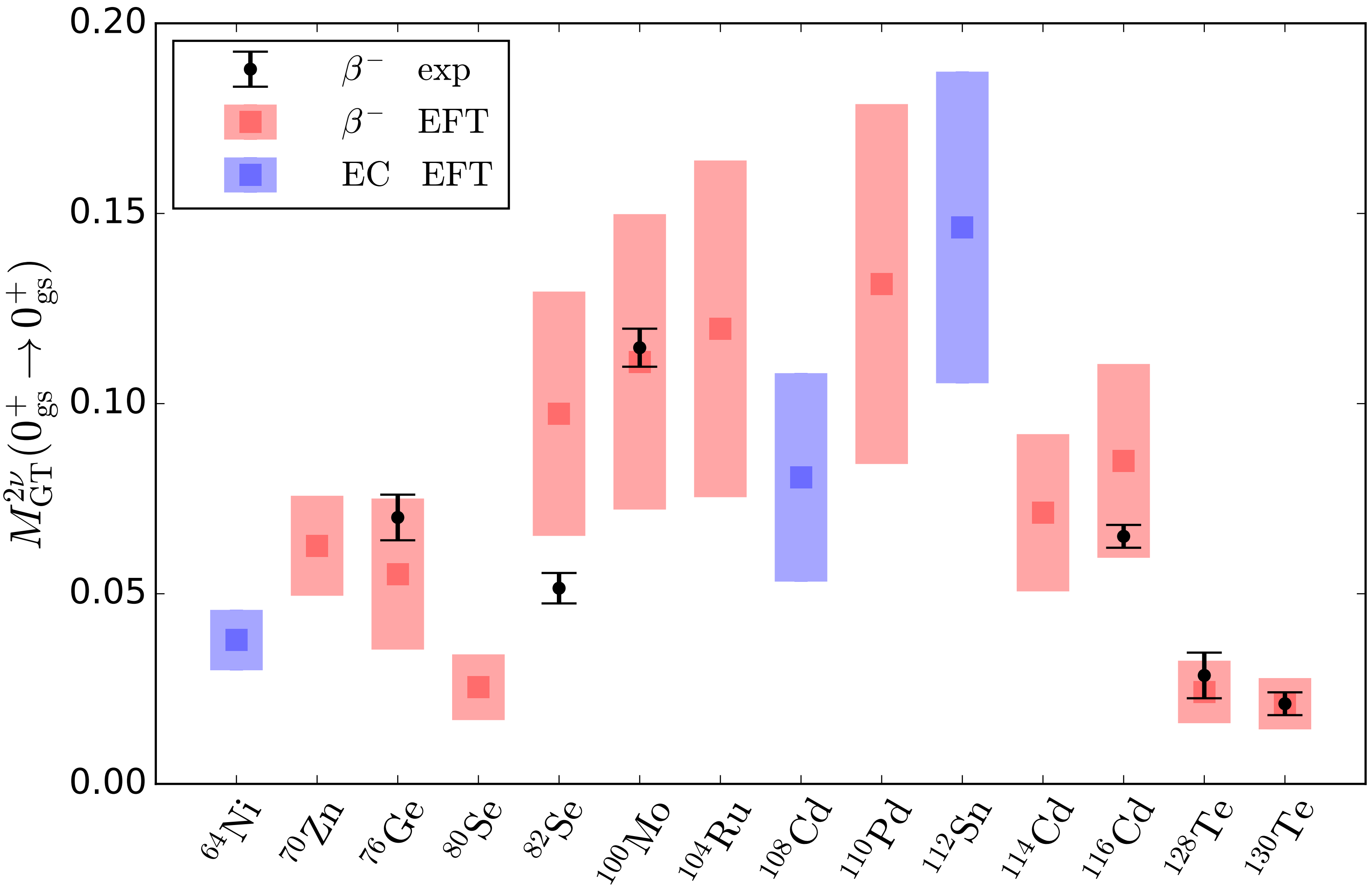
$$\begin{aligned}
&\Delta M^{2\nu}_{\text{GT}}(0^+_{\text{gs}} \to 0^+_{\text{gs}}) \\
&\overset{\text{EFT}}{\sim} \sum_{n=1} \left(\frac{\omega}{\Lambda}\right)^n \frac{M_{\text{GT}}(1^+_1 \to 0^+_{\text{gs}}) M_{\text{GT}}(0^+_{\text{gs}} \to 1^+_1)}{(D_{11} + n\omega)/m_e c^2} \\
&= \frac{D_{11}}{\Lambda} \Phi\left(\frac{\omega}{\Lambda}, 1, \frac{D_{11} + \omega}{\omega}\right) M^{2\nu}_{\text{GT}}(0^+_{\text{gs}} \to 0^+_{\text{gs}}) \,,
\end{aligned}$$

where

$$\Phi(z, s, a) \equiv \sum_{n=0}^{\infty} \frac{z^n}{(a+n)^s}$$

The percentual uncertainty depends on the energy scales involved transition

$$\delta(\text{gs} \to \text{gs}) = \frac{D_{11}}{\Lambda} \Phi\left(\frac{\omega}{\Lambda}, 1, \frac{D_{11} + \omega}{\omega}\right)$$



Coello Pérez, Menéndez, Schwenk; in preparation

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Summary and outlook

We studied single-β and $2\nu\beta\beta$ decays within a collective EFT

- Matrix elements for single-β decays to the ground and excited states of spherical nuclei can be consistently described within an EFT that describes the later systems as even-even collective cores coupled to an additional neutron and/or proton

- Matrix elements for $2\nu\beta\beta$ decays calculated within the SSD approximation consistently describe observed decays when the theoretical uncertainty estimate is taken into account

- NLO corrections to the Hamiltonian for the odd-odd system and the effective GT operator are expected to decrease the uncertainty by a factor of 1/3. These corrections are feasible

FUTURE GOAL

- Calculate matrix elements for $0\nu\beta\beta$ decays with uncertainty estimates. This would require us to write the corresponding operators in terms of the effective degrees of freedom. Since there is no available experimental data the LECs to other nuclear structure calculations, or highly correlated data

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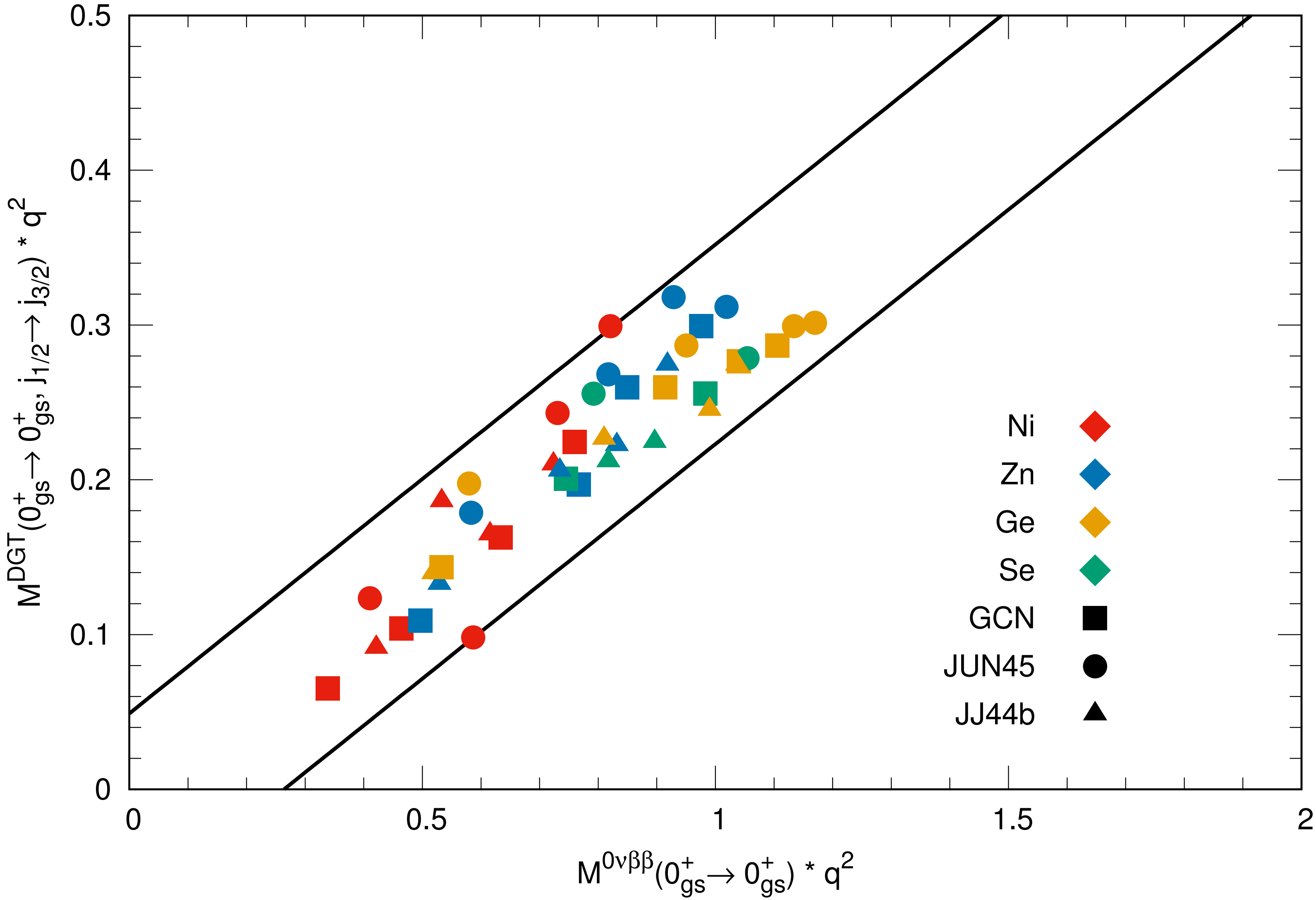

Thanks