Isospin-symmetry breaking correction to nuclear β-decay matrix elements for weak interaction studies

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Outline

1. Motivation
2. Shell-model formalism
3. Shell-model inputs
4. Superallowed $0^+ \to 0^+$ Fermi β decay
5. Gamow-Teller β decay

Collaborators

- Nadezda Smirnova (LP2I, Bordeaux),
- Michael Bender (LP2I, Lyon),
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- Frédérick Nowacki (IPHC, Strasbourg),
- Alex Brown (MSU, Michigan),
- Yi Hua Lam (IMP, Lanzhou).

Outline

Nucleus as a laboratory to study weak interaction

- Sperallowed $0^+ \to 0^+$ Fermi β decay of $T = 1$ nuclei (CVC, CKM unitarity)
- ~~Fermi β decay of mirror nuclei (alternative to the first process)~~
- Gamow-Teller β decay of mirror nuclei (search for $\mathcal{G}$-parity violating terms induced by nuclear structure)
- ~~First forbidden β decay (search for structure beyond the $V - A$ interaction)~~.

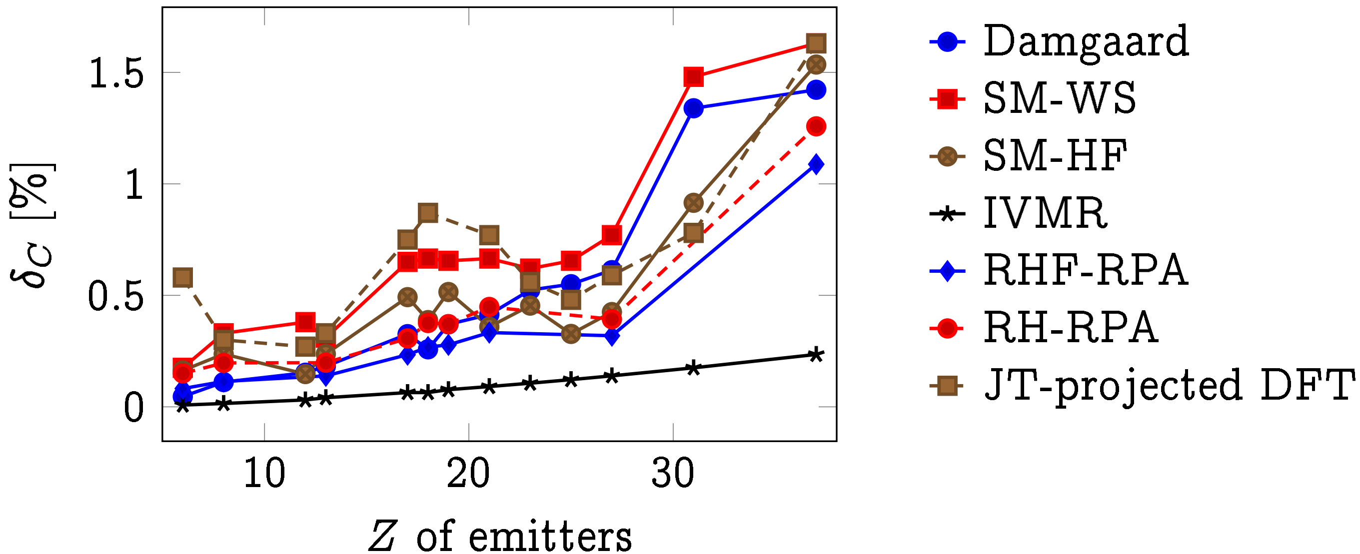
All this requires accurate description of the nuclear states, including isospin-symmetry breaking

Nucleus as a laboratory to study weak interaction

- Superallowed $0^+ \to 0^+$ Fermi β decay

$$Ft = ft(1+\delta'_R)(1-\delta_C+\delta_{NS}) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^V)}$$

δ_C has became a limiting factor in the extraction of V_{ud}:



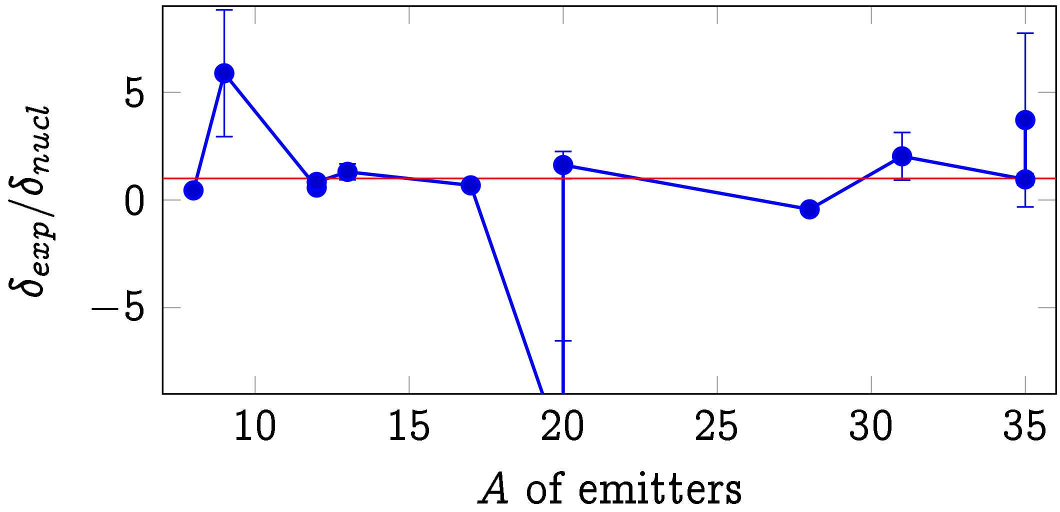
Towner, Hardy, PRC82, 065501 (2010)

Nucleus as a laboratory to study weak interaction

- Gamow-Teller β decay of mirror nuclei

$$\delta = \frac{(ft)_+}{(ft)_-} - 1 = \delta_{nucl} + \delta_{ssc}, \qquad \delta_{nucl} = \frac{(M^2)_-}{(M^2)_+} - 1$$

$\delta_{ssc} = 0$ if $\mathcal{G}$ parity is conserved by weak interaction.



Smirnova, Volpe, NPA714, 441 (2003)

Aims

- Derive exact shell-model formalism for δ_C (only *LO* terms were included in the previous calculations)
- Full model-space diagonalization (MCIA, University of Bordeaux, France)
- Existing well-established effective Hamiltonians (CKP, USD, GXPF1A, etc.)
- Selection of realistic basis functions (Woods-Saxon, Hartree-Fock)

Outline

Shell-model formalism

- Matrix element for a transition between $|i\rangle$ and $|f\rangle$,

$$M = \sum_{k_a k_b} \langle k_a \tau_a || \hat{O} || k_b \tau_b \rangle \, \mathrm{OBTD}(k_a \tau_a k_b \tau_b i f \lambda)$$

with

$$\mathrm{OBTD}(k_a \tau_a k_b \tau_b i f \lambda) = \frac{\langle f ||| [a^\dagger_{k_b \tau_b} \otimes \tilde{a}_{k_b \tau_b}]^{(\lambda)} || i \rangle}{\sqrt{2\lambda + 1}},$$

where λ is tensor rank of $\hat{O}$, and

$$\hat{O} = \begin{cases} \tau_\pm, & \text{for F} \\ \vec{\sigma}\tau_\pm, & \text{for GT} \end{cases}$$

the operator $\tau_\pm$ only connects 2 isobaric analogue states, whereas $\vec{\sigma}\tau_\pm$ involves a larger class of states

Shell-model formalism

The single-particle matrix element

$$\langle k_a \tau_a || \hat{O} || k_b \tau_b \rangle = \theta(l_a l_b j_a j_b) \Omega^{\tau_a \tau_b}_{k_a k_b} \xi_{\tau_a \tau_b}$$

with isospin component $\xi_{\tau_a \tau_b} = \langle \tau_a | \tau_\pm | \tau_b \rangle$, angular component

$$\theta(l_a l_b j_a j_b) = \begin{cases} \hat{j}_a \delta_{l_a l_b} \delta_{j_a j_b}, & \text{for F} \\ (-1)^{l_a + j_a + \frac{3}{2}} \sqrt{6} \hat{j}_a \hat{j}_b \left\{ \begin{array}{ccc} \frac{1}{2} & \frac{1}{2} & 1 \\ j_b & j_a & l_a \end{array} \right\} \delta_{l_a l_b}, & \text{for GT} \end{cases}$$

and radial component

$$\Omega^{\tau_a \tau_b}_{k_a k_b} = \int_0^\infty R^{\tau_a}_{k_a}(r) R^{\tau_a}_{k_b}(r) r^2 dr$$

this integral is slightly deviated from unity because of Coulomb repulsion between protons

Shell-model formalism

- To derive δ_C, we define

$$
\begin{aligned}
D(k_a\tau_a k_b\tau_b i f\lambda) &= \mathrm{OBTD}_0(k_a\tau_a k_b\tau_b i f\lambda) - \mathrm{OBTD}(k_a\tau_a k_b\tau_b i f\lambda) \\
\Lambda_{k_a k_b}^{\tau_a\tau_b} &= 1 - \Omega_{k_a k_b}^{\tau_a\tau_b}.
\end{aligned}
$$

then, rearrange M as

$$
\begin{aligned}
M = \quad & M_0\Big[1 - \frac{1}{M_0}\sum_{k_a k_b}\theta(l_a l_b j_a j_b)\Lambda_{k_a k_b}^{\tau_a\tau_b}\xi_{\tau_a\tau_b}\mathrm{OBTD}_0(k_a\tau_a k_b\tau_b i f\lambda) \\
- \quad & \frac{1}{M_0}\sum_{k_a k_b}\theta(l_a l_b j_a j_b)\xi_{\tau_a\tau_b} D(k_a\tau_a k_b\tau_b i f\lambda) \\
+ \quad & \frac{1}{M_0}\sum_{k_a k_b}\theta(l_a l_b j_a j_b)\Lambda_{k_a k_b}^{\tau_a\tau_b}\xi_{\tau_a\tau_b} D(k_a\tau_a k_b\tau_b i f\lambda)\Big].
\end{aligned}
$$

where M_0 is the isospin-symmetry matrix element.

Shell-model formalism

- According to $M^2 = M_0^2(1-\delta_C)$, we obtain $\delta_C = \sum_{i=1}^{6} \delta_{Ci}$ where

$$
\begin{aligned}
\delta_{C1} &= \frac{2}{M_0} \sum_{k_a k_b} \theta(l_a l_b j_a j_b) \xi_{\tau_a \tau_b} D(k_a \tau_a k_b \tau_b i f \lambda), \\
\delta_{C2} &= \frac{2}{M_0} \sum_{k_a k_b} \theta(l_a l_b j_a j_b) \Lambda_{k_a k_b}^{\tau_a \tau_b} \xi_{\tau_a \tau_b} \mathrm{OBTD}_0(k_a \tau_a k_b \tau_b i f \lambda), \\
\delta_{C3} &= -\frac{2}{M_0} \sum_{k_a k_b} \theta(l_a l_b j_a j_b) \Lambda_{k_a k_b}^{\tau_a \tau_b} \xi_{\tau_a \tau_b} D(k_a \tau_a k_b \tau_b i f \lambda), \\
\delta_{C4} &= -\frac{1}{4} \left(\delta_{C1} + \delta_{C2}\right)^2, \\
\delta_{C5} &= -\delta_{C3} \sqrt{|\delta_{C4}|}, \\
\delta_{C6} &= -\frac{1}{4} (\delta_{C3})^2.
\end{aligned}
$$

$\delta_{C1}, \delta_{C2} \equiv LO$, $\delta_{C3}, \delta_{C4} \equiv NLO$, $\delta_{C5} \equiv N^2LO$, $\delta_{C6} \equiv N^3LO$.

Shell-model formalism

- Therefore, the isospin-symmetry breaking occurs in 2 ways: $D(k_a\tau_a k_b\tau_b i f\lambda) \neq 0$ and $\Lambda^{\tau_a\tau_b}_{k_a k_b} \neq 0$.
- LO approximation

Both $D(k_a\tau_a k_b\tau_b i f\lambda)$ and $\Lambda^{\tau_a\tau_b}_{k_a k_b}$ are expected to be small, then

$$\delta_C \approx \delta_{C1} + \delta_{C2}$$

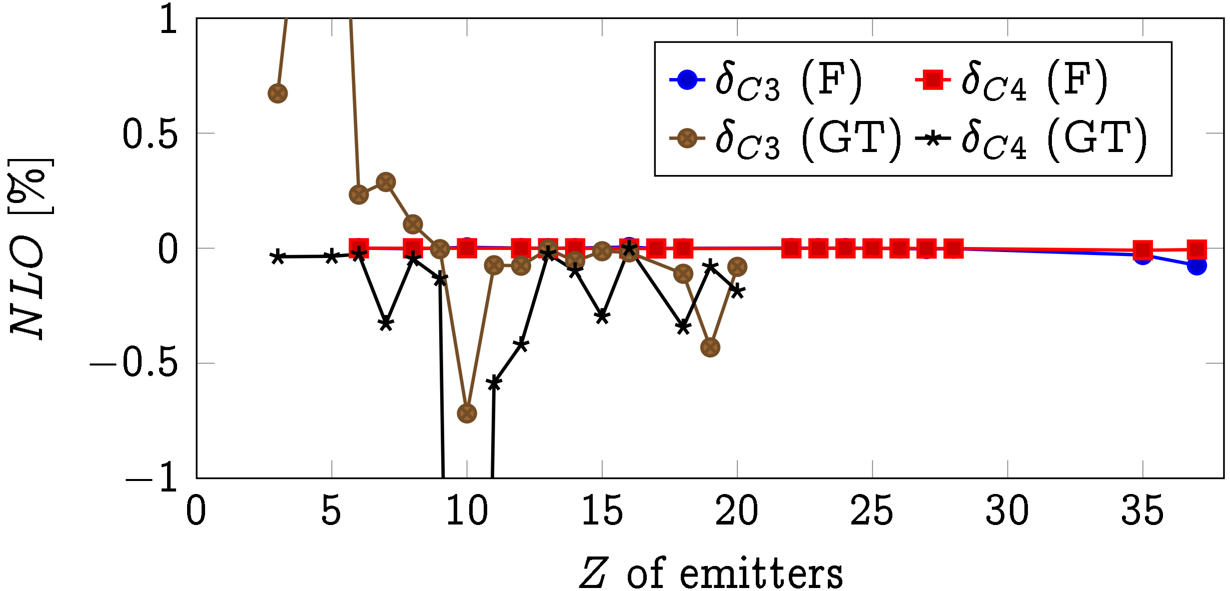
where δ_{C1} accounts for $D(k_a\tau_a k_b\tau_b i f\lambda) \neq 0$, whereas δ_{C2} accounts for $\Lambda^{\tau_a\tau_b}_{k_a k_b} \neq 0$.

Although this separation ansatz is convenient to handle, the higher order contribution has never been checked.

Towner, Hardy, PRC77, 025501 (2008)

Shell-model formalism

- Higher order contribution



NLO are negligible for F. Contrary it can be as large as 7 % for GT.

Xayavong, Smirnova, submitted to PRC.

Shell-model formalism

- We expand OBTDs in terms of intermediate states $|\pi\rangle$:

$$\text{OBTD}(k_a\tau_a k_b\tau_b i f \lambda) =$$

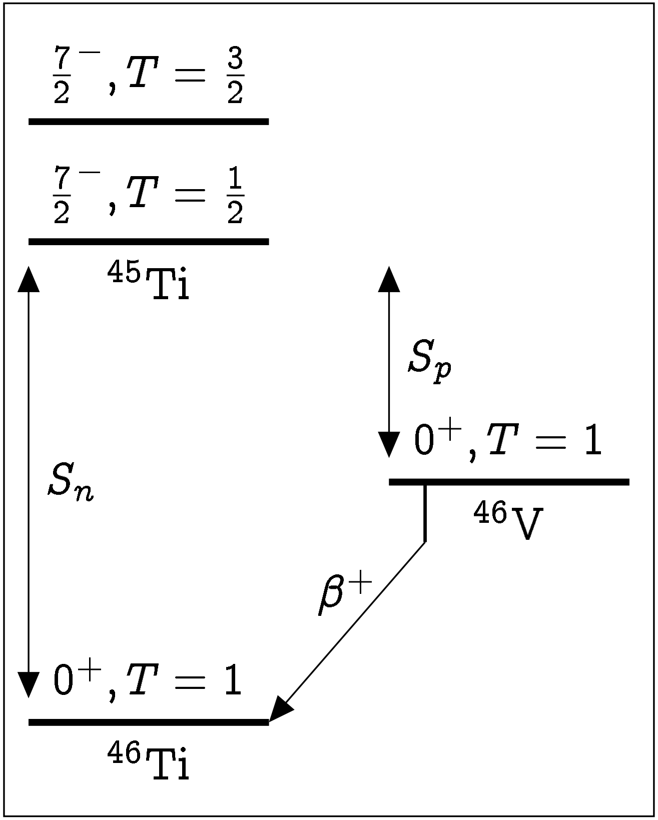
$$\sum_\pi \Theta(j_a j_b J_i J_f J_\pi \lambda)$$

$$\times \langle i || a^\dagger_{k_b\tau_b} || \pi\rangle \langle f || a^\dagger_{k_a\tau_a} || \pi\rangle \, ,$$

where

$$\Theta(j_a j_b J_i J_f J_\pi \lambda) =$$

$$(-1)^{J_f+J_\pi+j_a+\lambda} \begin{Bmatrix} J_i & J_f & \lambda \\ j_b & j_a & J_\pi \end{Bmatrix}$$



so that radial wave functions can be evaluted with excitation energies of $|\pi\rangle$

Shell-model formalism

- Subsequently δ_{C2}, δ_{C3} are evaluated as

$$\delta_{C2} = \frac{2}{M_0} \sum_{k_a k_b \pi} \theta(l_a l_b j_a j_b) \Lambda^{\tau_a \tau_b \pi}_{k_a k_b} \xi_{\tau_a \tau_b} \Theta(j_a j_b J_i J_f J_\pi \lambda) \times A_0(f; \pi k_a \tau_a) A_0(i; \pi k_b \tau_b),$$

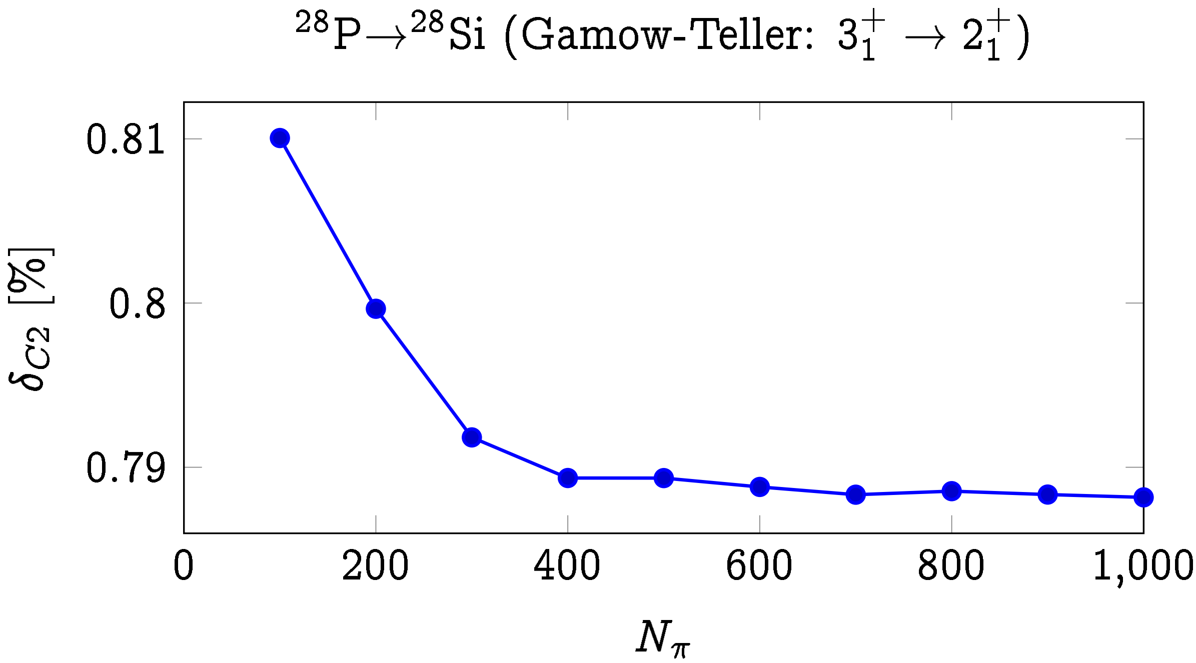
$$\delta_{C3} = -\delta_{C2} + \frac{2}{M_0} \sum_{k_a k_b \pi} \theta(l_a l_b j_a j_b) \Lambda^{\tau_a \tau_b \pi}_{k_a k_b} \xi_{\tau_a \tau_b} \times \Theta(j_a j_b J_i J_f J_\pi \lambda) A(f; \pi k_a \tau_a) A(i; \pi k_b \tau_b).$$

where

$$A(i; \pi k_b \tau_b) = \frac{\langle i || a^\dagger_{k_b \tau_b} || \pi \rangle}{\hat{J}_i}, \qquad A(f; \pi k_a \tau_a) = \frac{\langle f || a^\dagger_{k_a \tau_a} || \pi \rangle}{\hat{J}_f}$$

Shell-model formalism

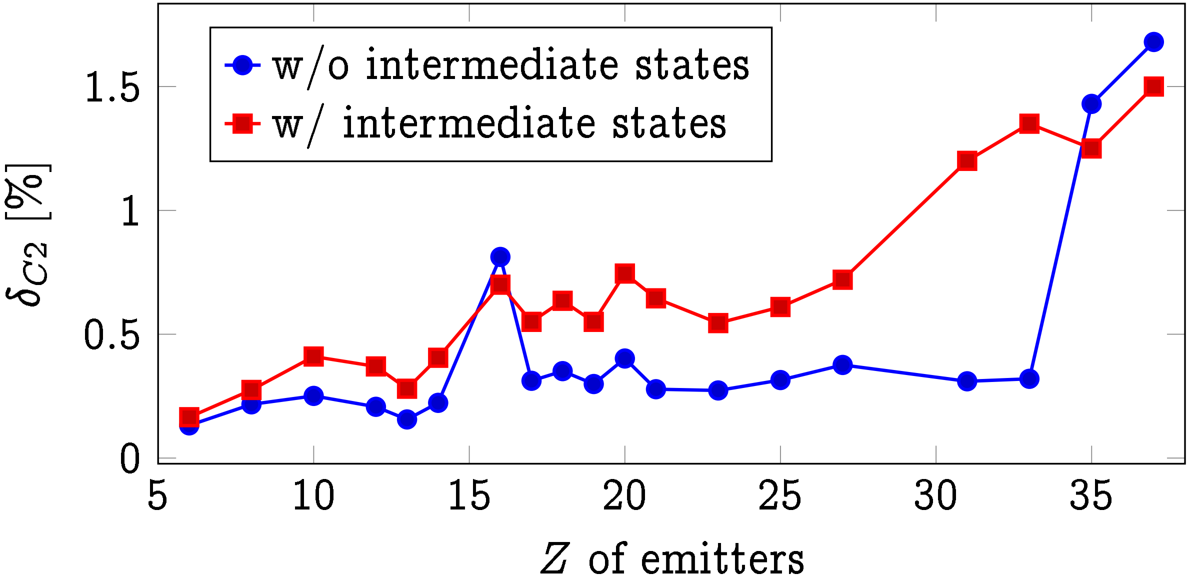
- Cut-off for the $\sum_{\pi}$



Usually, a thousand lowest states (for a given J^π) must be must be included. δ_{C3} converges much faster.

Shell-model formalism

- Influence of intermediate states



Usually δ_{C2} becomes larger and agrees better with the Standard Model, when intermediate states are included.

Towner, Hardy, PRC77, 025501 (2008)

Shell-model formalism

- Isospin structure of δ_{C2} for $T_i = T_f$ (F transitions)

$$\delta_{C2} = \frac{\sqrt{(T_i + 2t_{az}T_{iz} + 1)(T_i - 2t_{az}T_{iz})}}{T_i M_0} \sum_{k_a k_b} \theta(l_a l_b j_a j_b) \xi_{\tau_a \tau_b} \times \left[\sum_{\pi'} \Theta(j_a j_b J_i J_f J_{\pi'}) \Lambda_{k_a k_b}^{\tau_a \tau_b \pi'} \sqrt{S_0(f\pi' k_a) S_0(i\pi' k_b)} - \frac{T_i}{(T_i + 1)} \sum_{\pi''} \Theta(j_a j_b J_i J_f J_{\pi''}) \Lambda_{k_a k_b}^{\tau_a \tau_b \pi''} \sqrt{S_0(f\pi'' k_a) S_0(i\pi'' k_b)} \right],$$

where π' and π'' denote intermediate states with $T_\pi = T_i - \frac{1}{2}$ and $T_\pi = T_i + \frac{1}{2}$, respectively.

Smaller δ_{C2} is expected for Fermi transitions.

Shell-model formalism

- Isospin structure of δ_{C2} for $T_i \neq T_f$ (GT transitions)

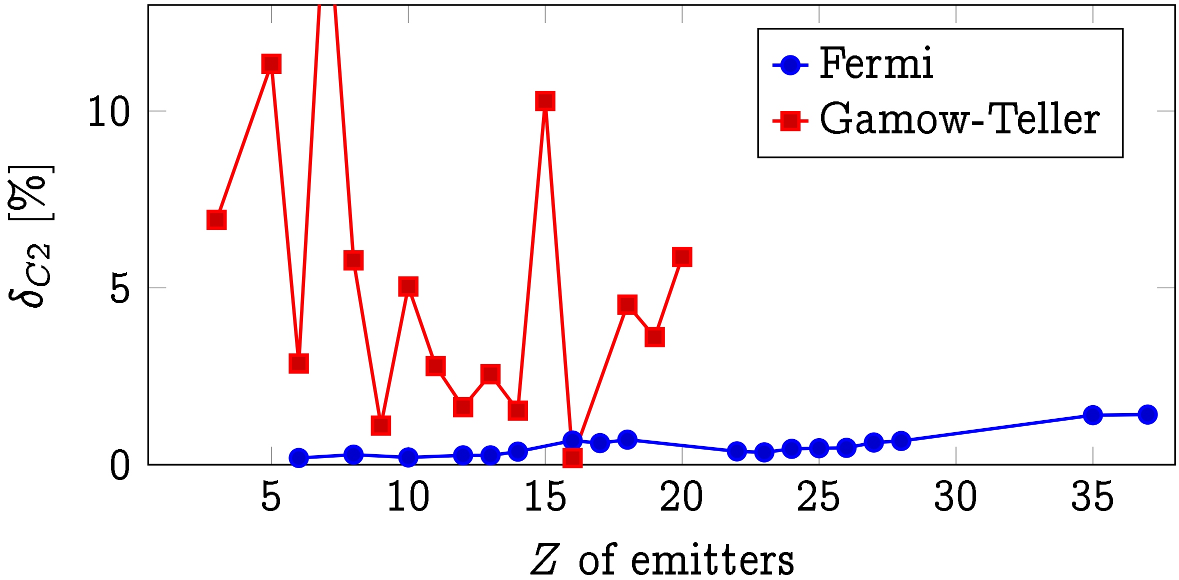
$$\delta_{C2} = -\frac{\sqrt{(T-2t_{az}T_{iz})(T+2t_{bz}T_{iz}+1)}}{(T+1)M_0} \times \sum_{k_a k_b \tilde{\pi}} \theta(l_a l_b j_a j_b)\Theta(j_a j_b J_i J_f J_{\tilde{\pi}})\Lambda^{\tau_a\tau_b\tilde{\pi}}_{k_a k_b}\xi_{\tau_a\tau_b}\sqrt{S_0(f\tilde{\pi}k_a)S_0(i\tilde{\pi}k_b)}.$$

$\tilde{\pi}$ denotes intermediate states with $T_\pi = T + \frac{1}{2}$ where $T = \min(T_i, T_f)$.

No cancellation occurs! Hence larger δ_{C2} is expected for GT.

Shell-model formalism

- Comparision of δ_{C2} for Fermi and Gamow-Teller transitions



In general, δ_{C2} for GT is much larger, and varies strongly from transition to transition.

Outline

Shell-model inputs

- Model spaces and effective Hamiltonians,

  Generally, the nuclear many-body problem cannot be solved in the full Hilbert space due to computational limit.

Hamiltonian	model space	mass range
CKPcd/CKIcd/CKIIcd	p shell	$A \leq 14$,
REWILcd/ZBMcd	$1p_{\frac{1}{2}}1d_{\frac{5}{2}}2s_{\frac{1}{2}}$	$15 \leq A \leq 22$,
USDcd/USDAcd/USDBcd	sd shell	$23 \leq A \leq 34$,
ZBM2+Coulomb	$2s_{\frac{1}{2}}1d_{\frac{3}{2}}1f_{\frac{7}{2}}2p_{\frac{3}{2}}$	$35 \leq A \leq 46$,
GXPF1Acd/FPD6cd/KB3Gcd	pf shell	$47 \leq A \leq 66$,
JUN45+Coulomb	$2p_{\frac{3}{2}}2p_{\frac{1}{2}}1f_{\frac{5}{2}}1g_{\frac{9}{2}}$	$A \geq 69$.

  We employ well-established empirical effective Hamiltonians

Shell-model inputs

- Woods-Saxon potential,

$$V(r) = -V_0 f(r, a_0, r_0) - V_0 \lambda \frac{\hbar^2}{4\mu^2 c^2} \frac{1}{r} \frac{d}{dr} f(r, a_s, r_s) \langle \boldsymbol{l}.\boldsymbol{\sigma} \rangle + V_{coul}(r)$$

with

$$V_{coul}(r) = (Z-1)e^2 \begin{cases} \frac{1}{r}, & r > R_c \\ \frac{1}{R_c}\left(\frac{3}{2} - \frac{r^2}{2R_c^2}\right), & \text{otherwise,} \end{cases}$$

R_c is extracted from charge radii R_{ch} via,

$$R_c^2 = \frac{5}{3} R_{ch}^2 + corr.\ terms$$

V_0 and r_0 are readjusted to fix separation energies and ch. radii, respectively.

Shell-model inputs

- Hartree-Fock potential using Skyrme interaction,

$$v_{Sk} = t_0(1 + x_0 P_\sigma)\delta + \frac{1}{2}t_1(1 + x_1 P_\sigma)(\mathbf{k}'^2\delta + \delta\mathbf{k}^2) + t_2(1 + x_2 P_\sigma)\mathbf{k}'.\delta\mathbf{k}$$
$$+\frac{1}{6}t_3(1 + x_3 P_\sigma)\rho^\alpha(\mathbf{R})\delta + iW_0(\sigma_i + \sigma_j).\mathbf{k}' \times \delta\mathbf{k} + v_{coul}$$

We employed the transformation $R^L_\alpha(r) = [m/m^*]^{\frac{1}{2}} R_\alpha(r)$ to get a local equivalent potential,

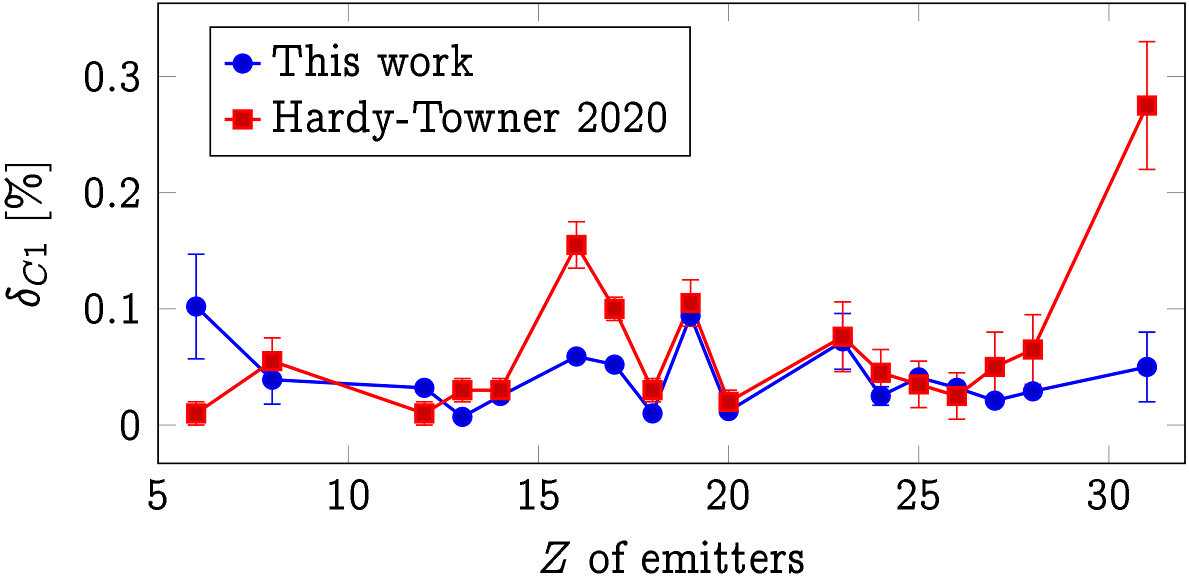
$$V^L(r, \epsilon_\alpha) = V^0(r, \epsilon_\alpha) + V^{so}(r)\langle \mathbf{l}.\sigma \rangle + V_{coul}(r)$$

then, scaling $V^0(r, \epsilon_\alpha)$ to reproduce separation energies.

Outline

Superallowed $0^+ \to 0^+$ Fermi β decay

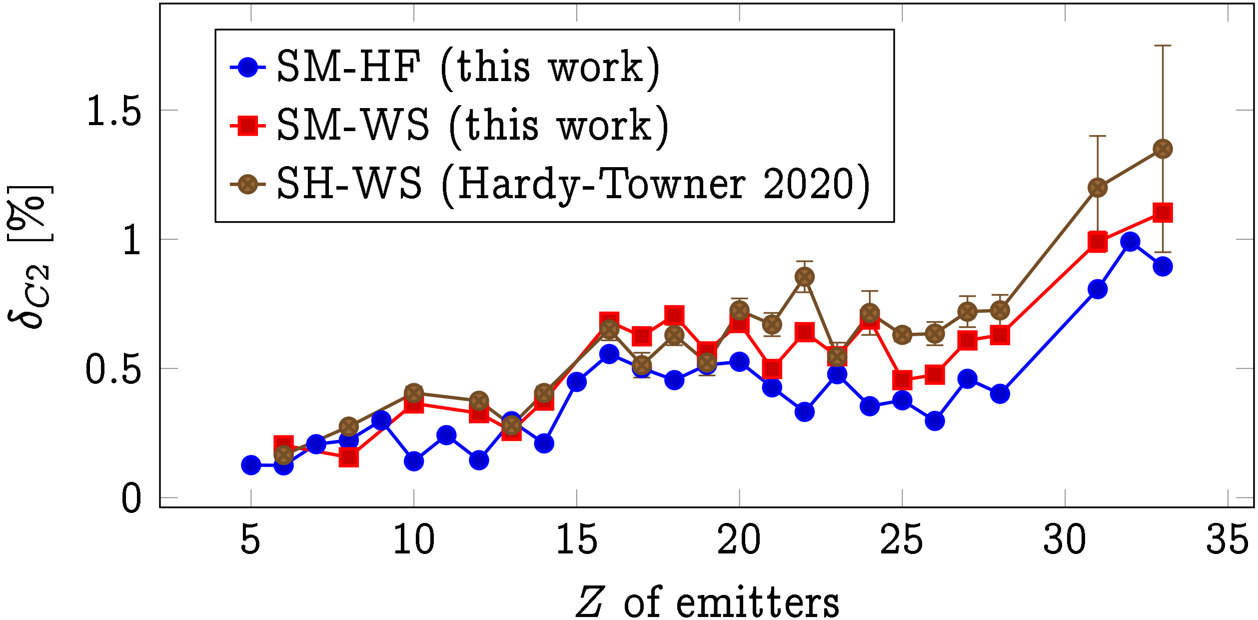
- Our preliminary result for δ_{C1}



HT readjusted interaction to reproduce IMME coefficients. Their result agrees very well with the Standard Model. Our values are too large for ^{10}C and too small for ^{30}S, ^{34}Cl, ^{62}Ga. The interactions obtained from a global fit are not accurate enough.

Superallowed $0^+ \to 0^+$ Fermi β decay

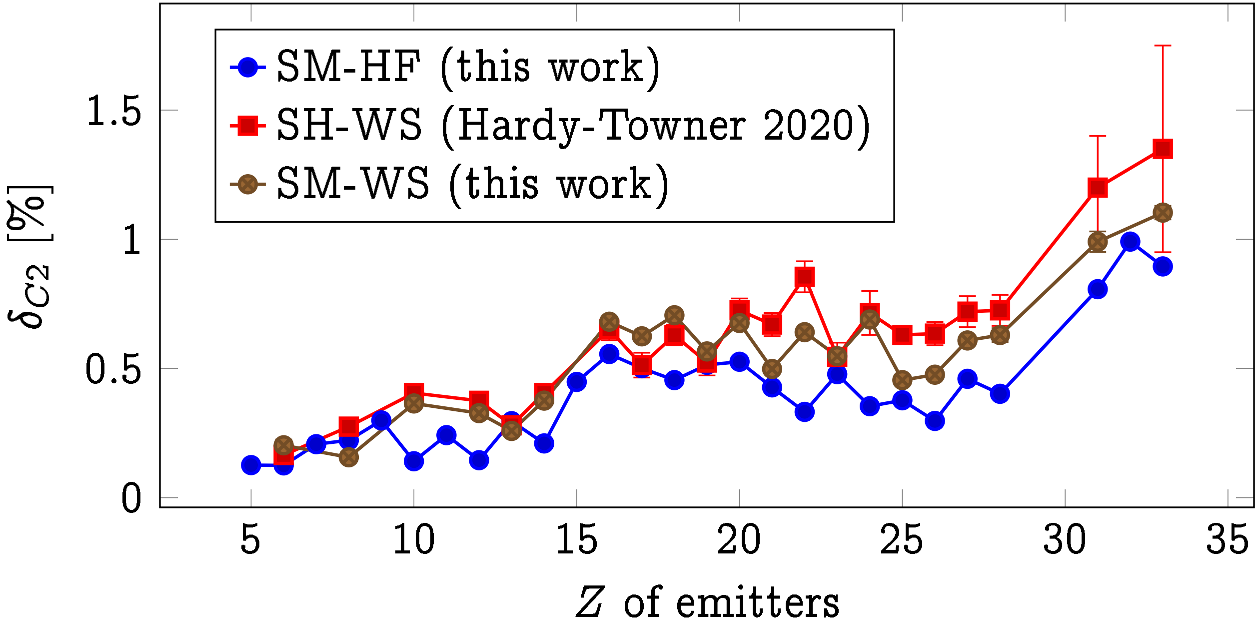
- The results for δ_{C2}



For SM-WS, our result agrees well with the latest result of Hardy-Towner, except for some cases in pf shell for which a full model space calculation is still challenging.

Superallowed $0^+ \to 0^+$ Fermi β decay

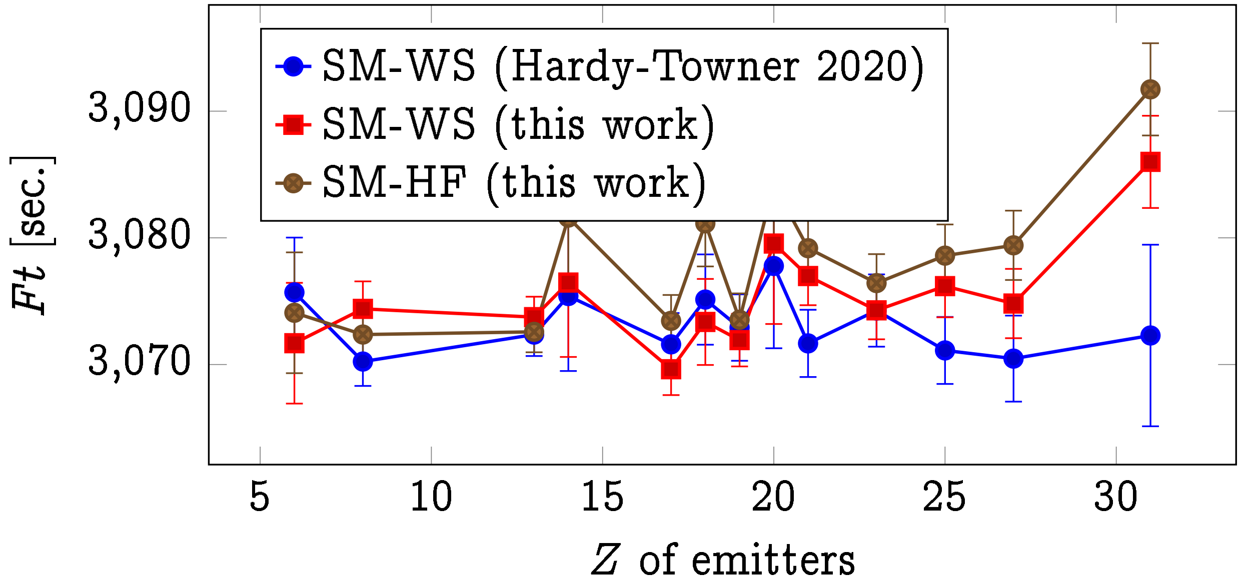
- The results for δ_{C2}



Unresolvable problem with HF: 1) sensitivity to beyond mean field contribution coming with readjustment, 2) spurious isospin mixing cannot be exactly suppressed.

Superallowed $0^+ \to 0^+$ Fermi β decay

- Constancy of corrected $\mathcal{F}t$



To make a test on an equal footing, data on (δ'_R, δ_{NS}) as well as theoretical uncertainties for δ_C are taken from Hardy, Towner, PRC102, 045501 (2020).

Superallowed $0^+ \rightarrow 0^+$ Fermi β decay

- Constancy of corrected $\mathcal{F}t$

Calculation	$\overline{\mathcal{F}t}$	χ^2/ν ($\nu = 14$)
SM-WS (Hardy-Towner 2020)	3073.15(75)	0.493
SM-WS (this work)	3075.31(71)	1.869
SM-HF (this work)	3078.33(71)	4.040

The latest result of Hardy-Towner agrees excellently with the CVC hypothesis. The large χ^2/ν value for SM-HF reflects the remaining problems in the SM-HF protocol.

Outline

Gamow-Teller β decay

- p shell nuclei

Transition	J_i^π, T_i	J_f^π, T_f	δ_{C1}	δ_{C2}	δ_{C3}	δ_{C4}
^{8}Li$(\beta^-)^8$Be	$2^+, 1$	$2_1^+, 0$	-10.775	6.925	0.673	-0.037
^{8}B$(\beta^+)^8$Be	$2^+, 1$	$2_1^+, 0$	-7.597	11.336	2.751	-0.035
^{9}Li$(\beta^-)^9$Be	$\frac{3}{2}^-, \frac{3}{2}$	$\frac{3}{2}{}_1^-, \frac{3}{2}$	-4.785	1.559	0.227	-0.026
^{9}C$(\beta^+)^9$B	$\frac{3}{2}^-, \frac{3}{2}$	$\frac{3}{2}{}_1^-, \frac{3}{2}$	-6.082	2.862	0.233	-0.026
^{12}B$(\beta^-)^{12}$C	$1^+, 1$	$0_1^+, 0$	-5.602	8.597	0.279	-0.022
^{12}N$(\beta^+)^{12}$C	$1^+, 1$	$0_1^+, 0$	-4.926	16.356	0.288	-0.327
^{13}B$(\beta^-)^{13}$C	$\frac{3}{2}^-, \frac{3}{2}$	$\frac{1}{2}{}_1^-, \frac{1}{2}$	-3.589	2.464	0.096	-0.003
^{13}O$(\beta^+)^{13}$N	$\frac{3}{2}^-, \frac{3}{2}$	$\frac{1}{2}{}_1^-, \frac{1}{2}$	-1.489	5.777	0.104	-0.046

- $p - sd$ cross shell nuclei

Transition	J_i^π, T_i	J_f^π, T_f	δ_{C1}	δ_{C2}	δ_{C3}	δ_{C4}
$^{17}N(\beta^-)^{17}O$	$\frac{1}{2}^-, \frac{3}{2}$	$\frac{3}{2}_1^-, \frac{1}{2}$	13.729	1.481	-0.166	-0.578
$^{17}Ne(\beta^+)^{17}F$	$\frac{1}{2}^-, \frac{3}{2}$	$\frac{3}{2}_1^-, \frac{1}{2}$	49.537	5.039	-0.718	-7.446
$^{20}F(\beta^-)^{20}Ne$	$2^+, 1$	$2_1^+, 0$	6.156	1.106	-0.004	-0.132
$^{20}Na(\beta^+)^{20}Ne$	$2^+, 1$	$2_1^+, 0$	12.516	2.787	-0.074	-0.585
$^{20}O(\beta^-)^{20}F$	$0^+, 2$	$1_1^+, 1$	9.079	0.368	-0.013	-0.223
$^{20}Mg(\beta^+)^{20}Na$	$0^+, 2$	$1_1^+, 1$	11.32	1.626	-0.076	-0.419
$^{21}F(\beta^-)^{21}Ne$	$\frac{5}{2}^+, \frac{3}{2}$	$\frac{3}{2}_1^+, \frac{1}{2}$	5.967	1.072	-0.052	-0.124
$^{21}Mg(\beta^+)^{21}Na$	$\frac{5}{2}^+, \frac{3}{2}$	$\frac{3}{2}_1^+, \frac{1}{2}$	8.775	2.898	-0.267	-0.341
$^{24}Ne(\beta^-)^{24}Na$	$0^+, 2$	$1_1^+, 1$	-3.316	0.252	-0.016	-0.023
$^{24}Si(\beta^+)^{24}Al$	$0^+, 2$	$1_1^+, 1$	4.742	1.529	-0.056	-0.098

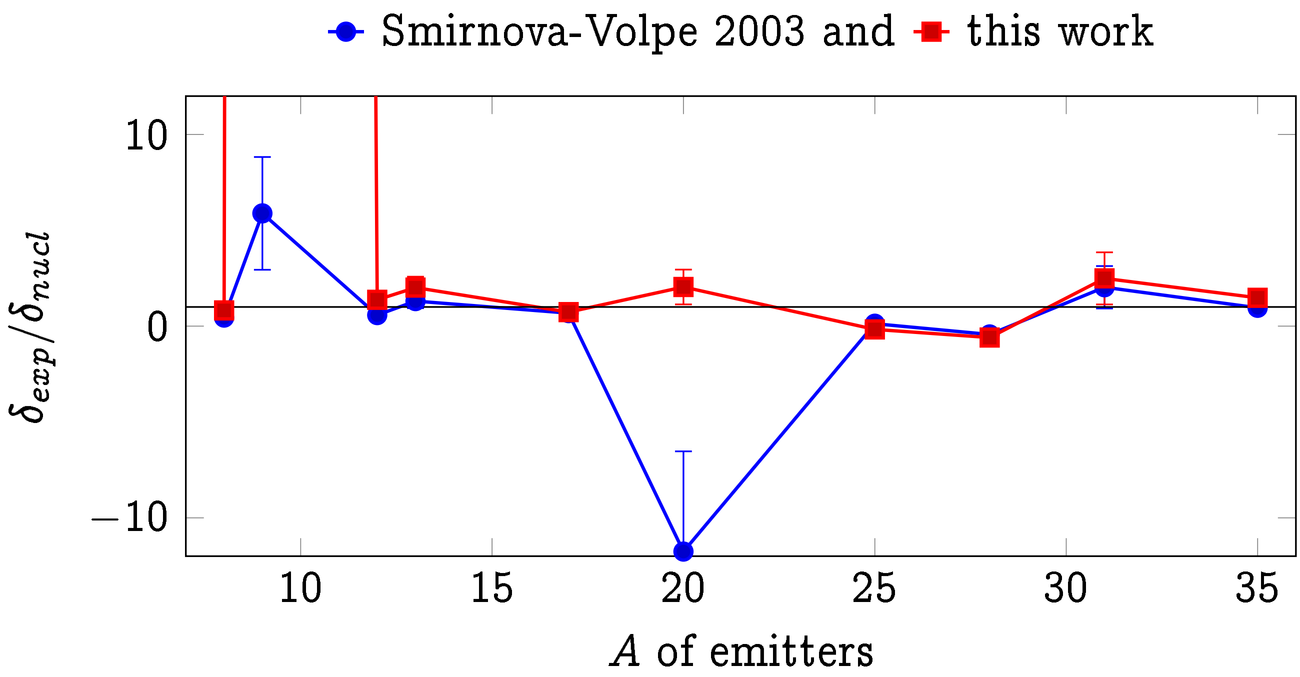
Gamow-Teller β decay

- *sd* shell nuclei

Transition	J_i^π, T_i	J_f^π, T_f	δ_{C1}	δ_{C2}	δ_{C3}	δ_{C4}
$^{25}\mathrm{Na}(\beta^-)^{25}\mathrm{Mg}$	$\frac{5}{2}^+, \frac{3}{2}$	$\frac{5}{2}^+_1, \frac{1}{2}$	1.328	0.545	-0.014	-0.009
$^{25}\mathrm{Si}(\beta^+)^{25}\mathrm{Al}$	$\frac{5}{2}^+, \frac{3}{2}$	$\frac{5}{2}^+_1, \frac{1}{2}$	0.741	0.301	0.001	-0.003
$^{28}\mathrm{Al}(\beta^-)^{28}\mathrm{Si}$	$3^+, 1$	$2^+_1, 0$	0.547	2.558	-0.004	-0.024
$^{28}\mathrm{P}(\beta^+)^{28}\mathrm{Si}$	$3^+, 1$	$2^+_1, 0$	0.621	10.285	-0.013	-0.297
$^{31}\mathrm{Al}(\beta^-)^{31}\mathrm{Si}$	$\frac{5}{2}^+, \frac{5}{2}$	$\frac{3}{2}^+_1, \frac{3}{2}$	-1.77	1.261	0.023	-0.001
$^{31}\mathrm{Ar}(\beta^+)^{31}\mathrm{Cl}$	$\frac{5}{2}^+, \frac{5}{2}$	$\frac{3}{2}^+_1, \frac{3}{2}$	7.186	4.527	-0.111	-0.343
$^{35}\mathrm{S}(\beta^-)^{35}\mathrm{Cl}$	$\frac{3}{2}^+, \frac{3}{2}$	$\frac{3}{2}^+_1, \frac{1}{2}$	0.052	0.187	-0.018	0
$^{35}\mathrm{K}(\beta^+)^{35}\mathrm{Ar}$	$\frac{3}{2}^+, \frac{3}{2}$	$\frac{3}{2}^+_1, \frac{1}{2}$	2.045	3.607	-0.431	-0.08
$^{35}\mathrm{P}(\beta^-)^{35}\mathrm{S}$	$\frac{1}{2}^+, \frac{5}{2}$	$\frac{1}{2}^+_1, \frac{3}{2}$	-3.322	0.531	0.017	-0.019
$^{35}\mathrm{Ca}(\beta^+)^{35}\mathrm{K}$	$\frac{1}{2}^+, \frac{5}{2}$	$\frac{1}{2}^+_1, \frac{3}{2}$	2.755	5.875	-0.081	-0.186

Gamow-Teller β decay

- Asymmetry of mirror Gamow-Teller β decays



We got a better result for $A = 20$.

Summary

- W have derived a suitable exact shell-model formalism for δ_C
- Our shell-model diagonalizations were performed in full model spaces
- δ_{C1} is strongly interaction-dependent (generally, a global fitted interactions do not work)
- Calculation using Woods-Saxon basis (SM-WS) agrees well with the Standard Model
- Hartree-Fock suffers from a number of deficiencies (correlations, spontaneous symmetry breaking)
- Understanding of the isospin-symmetry breaking mechanism in Fermi and Gamow-Teller transitions