

Shell-Model study of the isospin-symmetry breaking correction to superallowed $0^+ \rightarrow 0^+$ β -decay

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Building Together for the Future"

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Introduction

Superallowed $0^+ \rightarrow 0^+$ Fermi β -decay is an important tool to test the Standard Model of elementary particles and their interactions :

- test of the Conserved Vector Current (CVC) hypothesis \Rightarrow vector coupling constant for a semi-leptonic decay G_V

$$ft^{0^+ \rightarrow 0^+} = \frac{K}{|M_F^0|^2 G_V^2}$$

$$K = \frac{2\pi^3 \ln 2 \hbar^7 c^6}{(m_e c^2)^5}, \quad |M_F^0| = \sqrt{T(T+1) - T_{zi} T_{zf}}$$

- check of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix

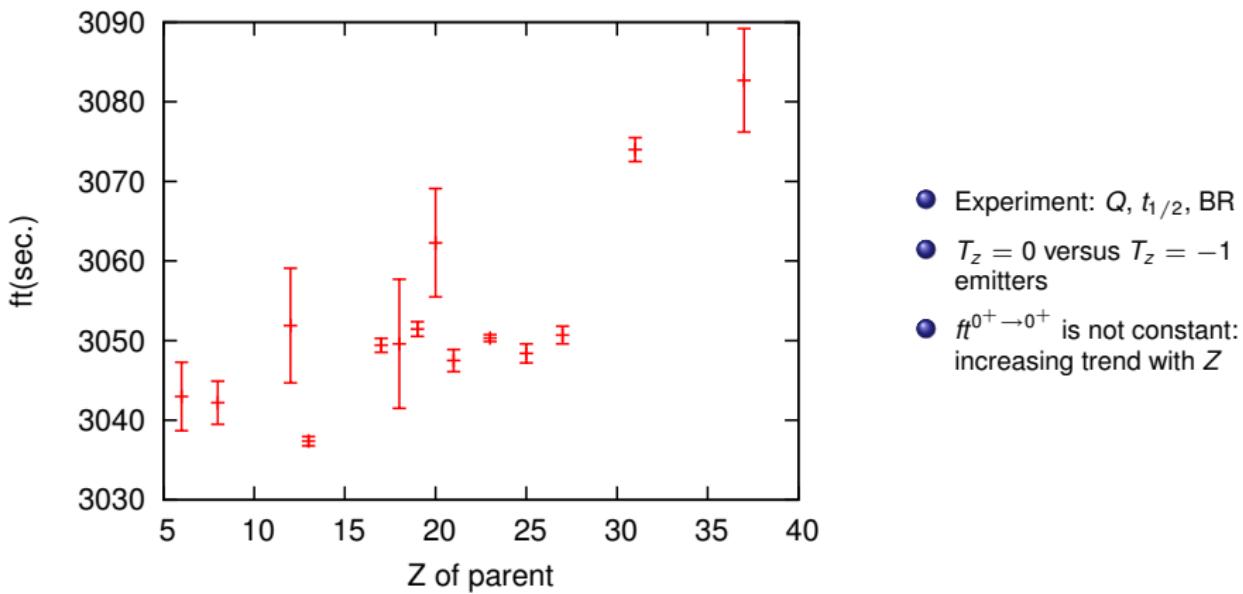
$$|V_{ud}| = G_V/G_V^\mu$$

$ft^{0^+ \rightarrow 0^+}$ -values from the experiment

14 best known emitters ($ft^{0^+ \rightarrow 0^+}$ -value known with a precision $\lesssim 0.4\%$):

^{10}C , ^{14}O , ^{22}Mg , ^{26m}Al , ^{34}Cl , ^{34}Ar , ^{38m}K , ^{38}Ca , ^{42}Sc , ^{46}V , ^{50}Mn , ^{54}Co , ^{62}Ga , ^{74}Rb

J.C. Hardy, I.S. Towner, PRC91, 025501 (2015)



Introduction

Absolute Ft value

$$Ft^{0^+ \rightarrow 0^+} \equiv ft^{0^+ \rightarrow 0^+} (1 + \delta'_R)(1 + \delta_{NS} - \delta_C) = \frac{K}{|M_F^0|^2 G_V^2 (1 + \Delta_R)}$$

14 best known emitters (ft -value known with a precision $\lesssim 0.1\%$):

^{10}C , ^{14}O , ^{22}Mg , ^{26m}Al , ^{34}Cl , ^{34}Ar , ^{38m}K , ^{38}Ca , ^{42}Sc , ^{46}V , ^{50}Mn , ^{54}Co , ^{62}Ga , ^{74}Rb

J.C. Hardy, I.S. Towner, PRC91, 025501 (2015)

Radiative corrections

$$\begin{aligned}\Delta_R^V &= (2.361 \pm 0.038)\% \\ \delta'_R &\approx 1.5 \pm \sim 0.15\% \\ |\delta_{NS}| &\lesssim 0.3\%\end{aligned}$$

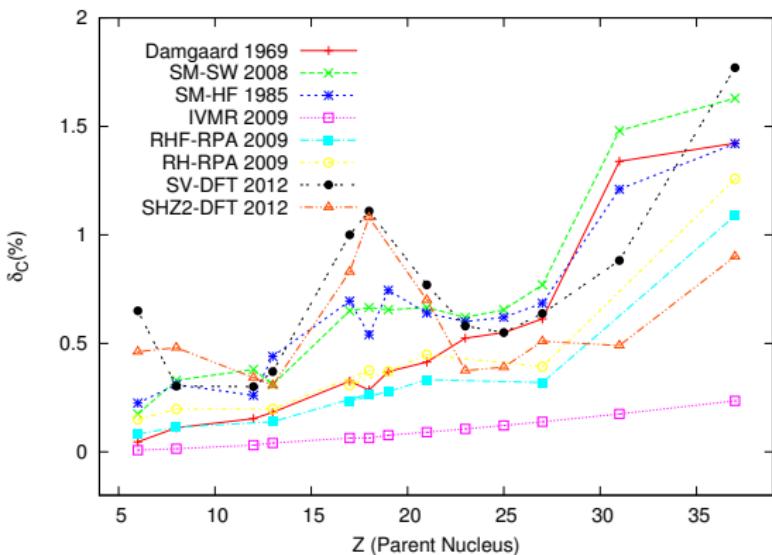
A. Sirlin, W.J. Marciano,
W. Jaus, G. Rasche

Nuclear-structure correction

$$\begin{aligned}|M_F|^2 &= |M_F^0|^2 (1 - \delta_C) \\ |M_F^0|^2 &= T(T+1) - T_{zi} T_{zf} \\ \delta_C &\approx 0.1 - 2.0\%\end{aligned}$$

δ_C — large ambiguities from various theoretical models

Present status of δ_C from various models



- Damgaard Model (Damgaard)
- Shell Model (WS - Towner, Hardy; HF – Ormand, Brown)
- RHF-RPA and RH-RPA (N. Van Giai et al)
- JT-projected HF (W. Satula et al)
- Isovector Monopole Resonance (N. Auerbach)

Shell-model study of δ_C

Existing work within the shell model

- I.S. Towner, J.C. Hardy (1973 – 2015)
Phys. Rev. C91, 025501 (2015) and refs. therein
- W.E. Ormand, B.A. Brown (1985 – 1995)
NPA440 (1985); PRL62 (1989); PRC52 (1995)

The aim of the present work:

- Large-scale calculations
- New effective interactions
- Revision of constraints on single-particle potentials
- HF radial wave functions

Formalism

Exact diagonalization of the effective Hamiltonian matrix

$$\hat{H}|\Psi_p\rangle = (\hat{H}^{(0)} + \hat{V}) |\Psi_p\rangle = E_p |\Psi_p\rangle$$

$$|\Psi_p\rangle = \sum_{k=1}^n c_{pk} |\Phi_k\rangle, \quad \hat{H}^{(0)} |\Phi_k\rangle = E_k^{(0)} |\Phi_k\rangle$$

$$H_{lk} = \langle \Phi_l | \hat{H} | \Phi_k \rangle = E_k^{(0)} \delta_{lk} + V_{lk} \quad \forall (J, T) \Rightarrow \{E_p, c_{pk}\}$$

- NuShellX@MSU shell-model code (W.D.M. Rae, B.A. Brown).
- Antoine shell-model code (E. Caurier).

Fermi β -decay matrix element

$$M_F = \sum_{\alpha} \langle \Psi_f | a_{\alpha n}^\dagger a_{\alpha p} | \Psi_i \rangle \langle \alpha_n | t_+ | \alpha_p \rangle$$

$$\langle \Psi_f | a_{\alpha n}^\dagger a_{\alpha p} | \Psi_i \rangle = \frac{\langle \omega_f J_f | a_{\alpha n}^\dagger a_{\alpha p} | \omega_i J_i \rangle}{\sqrt{2J_f + 1}} \equiv \Delta_{\alpha}$$

$$\langle \alpha_n | t_+ | \alpha_p \rangle = \int_0^\infty R_{\alpha n}(r) R_{\alpha p}(r) r^2 dr \equiv \Omega_{\alpha}$$

$$\alpha = (n_{\alpha}, l_{\alpha}, j_{\alpha})$$

G.A. Miller, A. Schwenk,

Exact Fermi operator: $n_{\alpha n} \neq n_{\alpha p}$

PRC78 (2008); PRC80 (2009)

Isospin symmetry breaking

Isospin-symmetry limit

$$M_F^0 = \sum_{\alpha} \Delta_{\alpha}^T \Omega_{\alpha}^T = \sqrt{T(T+1) - T_{zi} T_{zf}}, \quad \Omega_{\alpha}^T = 1$$

Realistic model (Coulomb and charge-symmetry breaking effective nuclear forces)

$$M_F = \sum_{\alpha} \Delta_{\alpha} \Omega_{\alpha}$$

$$M_F = M_F^0 \left[1 - \frac{1}{M_F^0} \sum_{\alpha} (\Delta_{\alpha}^T - \Delta_{\alpha}) - \frac{1}{M_F^0} \sum_{\alpha} \Delta_{\alpha}^T (1 - \Omega_{\alpha}) + \frac{1}{M_F^0} \sum_{\alpha} (\Delta_{\alpha}^T - \Delta_{\alpha}) (1 - \Omega_{\alpha}) \right]$$

$$|M_F|^2 \approx |M_F^0|^2 \left[1 - \underbrace{\frac{2}{M_F^0} \sum_{\alpha} (\Delta_{\alpha}^T - \Delta_{\alpha})}_{\delta_{IM}} - \underbrace{\frac{2}{M_F^0} \sum_{\alpha} \Delta_{\alpha}^T (1 - \Omega_{\alpha})}_{\delta_{RO}} \right],$$

$$\delta_C = \delta_{IM} + \delta_{RO}$$

- δ_{IM} is the *isospin-mixing* part
- δ_{RO} is the *radial-overlap* part

I. Isospin-mixing correction δ_{IM}

- Isospin-nonconserving (INC) Hamiltonian

$$\hat{H}_{INC}\Psi \equiv (\hat{H}_0 + \hat{V} + \hat{V}_{INC})\Psi = E\Psi$$

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- We start with an isospin-symmetry invariant shell-model Hamiltonian $[\hat{H}, \hat{T}] = 0$

$$\hat{H}\Psi_{TT_z} \equiv (\hat{H}_0 + \hat{V})\Psi_{TT_z} = E_T\Psi_{TT_z}, \quad \Psi_{TT_z} = \sum_k a_{T_k} \Phi_{TT_z k}$$

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- We consider an isospin-symmetry non-conserving term

$$\hat{V}_{INC} = \underbrace{\lambda_C \hat{V}_C}_{Coulomb} + \underbrace{\lambda_1 \hat{V}^{(1)}}_{isovector} + \underbrace{\lambda_2 \hat{V}^{(2)}}_{isotensor} + \underbrace{\hat{H}_0^{IV}}_{\sum_\alpha (\varepsilon_\alpha^p - \varepsilon_\alpha^n)}$$

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- Within perturbation theory:

$$\langle \Psi_{TT_z} | \hat{V}_{INC} | \Psi_{TT_z} \rangle = E^{(0)}(\alpha, T) + E^{(1)}(\alpha, T)T_z + E^{(2)}(\alpha, T) [3T_z^2 - T(T+1)]$$

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- Fit to experimental coefficients of the Isobaric Mass Multiplet Equation (IMME):

$$M(\alpha, T, T_z) = a(\alpha, T) + b(\alpha, T)T_z + c(\alpha, T)T_z^2,$$

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- We consider an isospin-symmetry non-conserving term

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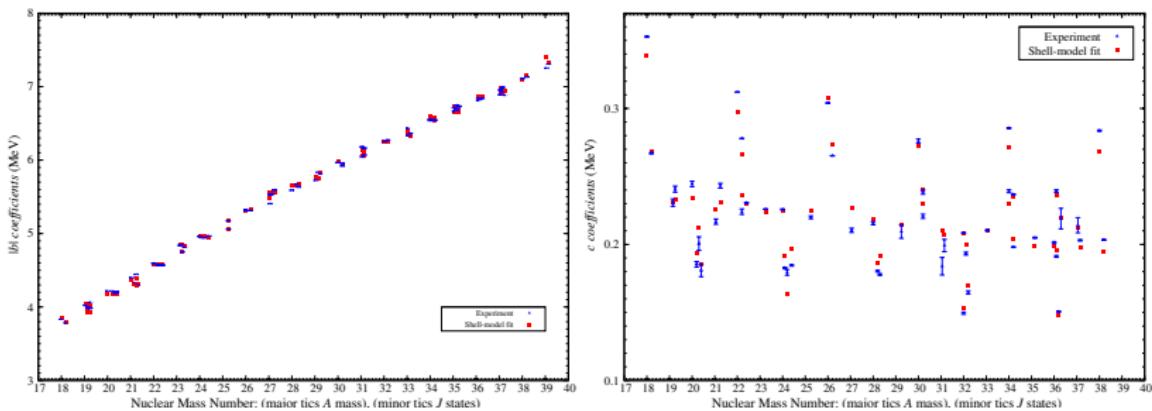
- Diagonalization of the INC Hamiltonian $[\hat{H}_{INC}, \hat{T}] \neq 0$:

$$\hat{H}_{INC}\Psi = E\Psi$$

Results of the fit of b and c coefficients in sd -shell

$$M(\alpha, T, T_z) = a(\alpha, T) + b(\alpha, T)T_z + c(\alpha, T)T_z^2$$

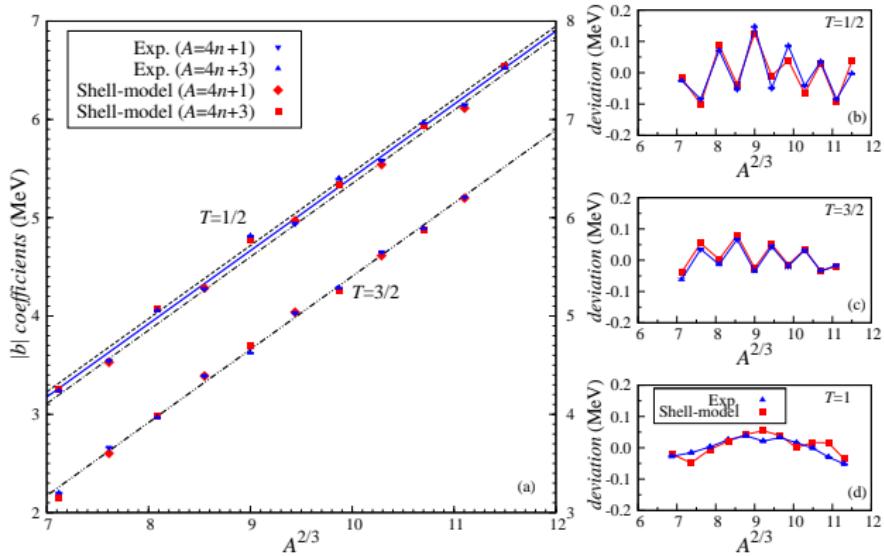
USD (B.H. Wildenthal, 1988) or USDA/USDB (B.A. Brown, W.A. Richter, 2006)
plus the INC term (\hat{V}_C , \hat{V}_ρ or $\hat{V}^{T=1}$, \hat{H}_0^{IV})



- b coefficients ($v_{pp} - v_{nn}$); 81 data points ($T = 1/2, 1, 3/2, 2$); rms ≈ 32 keV
- c coefficients ($v_{pp} + v_{nn} - 2v_{pn}$); 51 data points ($T_z = 1, 3/2, 2$); rms ≈ 10 keV

Staggering of b -coefficients of sd -shell nuclei

J.Jänecke, 1966, 1969; K.T.Hecht, 1968; Y.H.Lam, N.S., E.Caurier, 2013



Shell-model values of the isospin-mixing correction (δ_{IM})

$$\delta_{IM} = \delta_{IM}^{th} \left(\frac{\Delta E^{th}}{\Delta E^{exp}} \right)^2$$

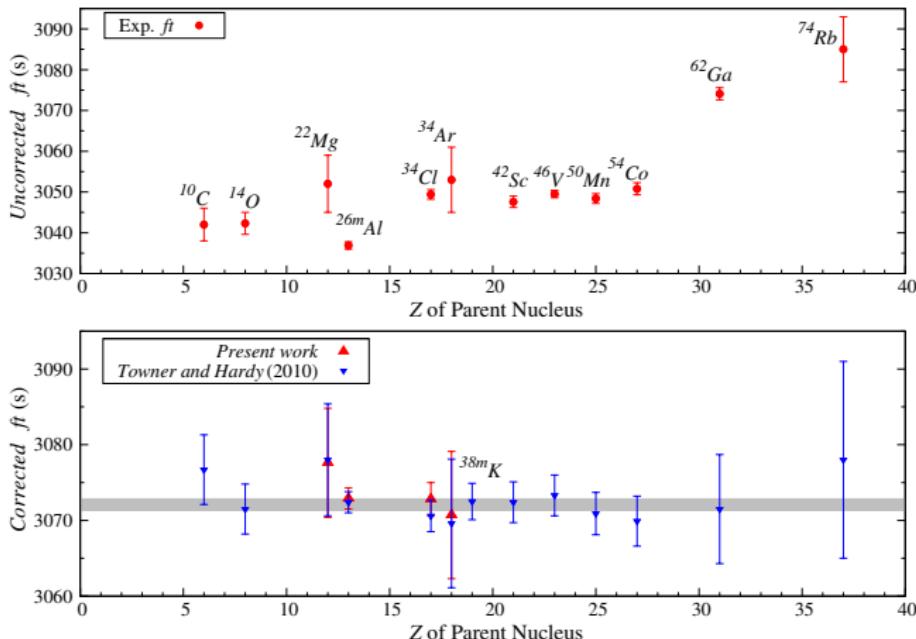
Present results: USD interaction plus V_{INC}

Emitter	δ_{IM}		$\mathcal{F}t$		
	Present work (2013)	Ormand, Brown (1989)	Towner, Hardy (2008)	Present work (2013)	Towner, Hardy (2010)
^{22}Mg	0.0216(9)	0.017	0.010 (10)	3077.6(72)	3077.6(74)
^{26m}Al	0.0120(8)	0.01	0.025 (10)	3072.9(13)	3072.4(14)
^{26}Si	0.046(0)	0.028	0.022 (10)		
^{30}S	0.027(1)	0.056	0.137 (20)		
^{34}Cl	0.0363(5)	0.06	0.091 (10)	3072.6(21)	3070.6(21)
^{34}Ar	0.0060(4)	0.008	0.023 (10)	3070.7(84)	3069.6(85)

Y. Lam, N. S., E. Caurier, PRC87 (2013)

Ft values of 13 best known $0^+ \rightarrow 0^+$ transitions

Towner, Hardy, Rep. Prog. Phys. 73, 2010; Y.H. Lam, N.S., E. Caurier, PRC87, 2013



II. Radial overlap correction

Beyond the closure approximation

$$\delta_{RO} = \frac{2}{M_F^0} \sum_{\alpha} \langle \Psi_f | a_{\alpha n}^\dagger a_{\alpha p} | \Psi_i \rangle^T (1 - \Omega_{\alpha})$$

↓

$$\delta_{RO} = \frac{2}{M_F^0} \sum_{\alpha, \pi} \langle \Psi_f | a_{\alpha n}^\dagger | \pi \rangle^T \langle \pi | a_{\alpha p} | \Psi_i \rangle^T (1 - \Omega_{\alpha}^\pi)$$

Two ingredients:

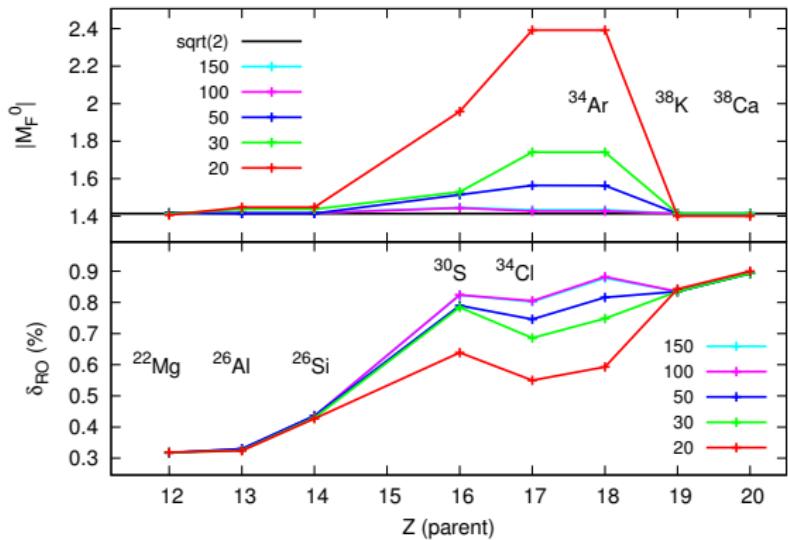
- *Spectroscopic amplitudes* (from the shell-model or from experiment):

$$\langle \Psi_f | a_{\alpha n}^\dagger | \pi \rangle = \frac{\langle \Psi_f || a_{\alpha n}^\dagger || \pi \rangle}{\sqrt{2J_f + 1}}$$

- *Radial-overlap integrals* (from a realistic single-particle potential)

$$\Omega_{\alpha} = \int_0^{\infty} R_{\alpha n}^\pi(r) R_{\alpha p}^\pi(r) r^2 dr$$

Convergence of M_F and δ_{RO}



- Convergence of δ_{RO} is faster than that of M_F .
- $N_\pi = 100$.

- sd -shell: USD (Wildenthal, 1984) and USDA/USDB (B.A.Brown, W.A. Richter, 2006)
- pf -shell: KB3G (A. Poves et al, 2004) and GXPF1A (M. Honma et al, 2004).
- $pf_{5/2}g_{9/2}$: JUN45 (Honma et al, 2009).

Woods-Saxon potential

Phenomenological WS potential

$$V(r) = V_0 f(r, R_0, a_0) + V_s \left(\frac{r_s}{\hbar} \right)^2 \frac{1}{r} \frac{d}{dr} [f(r, R_s, a_s)] (\mathbf{I} \cdot \boldsymbol{\sigma}) + V_{sym}(r) + V_C(r)$$

$$f(r, R_i, a_i) = \frac{1}{1 + \exp \left(\frac{r - R_i}{a_i} \right)}, \quad V_s = \lambda V_0$$

Symmetry term:

$$V_{sym}(r) = V_1 \frac{(\mathbf{t} \cdot \mathbf{T}')}{A - 1} f(r, R_0, a_0)$$

Coulomb term:

$$V_C(r) = (Z - 1)e^2 \times \begin{cases} \frac{1}{r}, & \text{if } r > R_C; \\ \frac{1}{R_C} \left(\frac{3}{2} - \frac{r^2}{2R_C^2} \right), & \text{otherwise.} \end{cases}$$

Two parametrizations:

- A. Bohr, B.R. Mottelson modified (BM_m) from *Nuclear Structure, Vol. I.*
- N. Schwierz, I. Wiedenhöver, A. Volya (SWV) from *nucl-th:0709.3525 (2007)*

$a = a_s = 0.662 \text{ fm}$, $R = r_0 (A - 1)^{1/3}$, $R_s = r_s (A - 1)^{1/3}$ with $r_s = 1.16 \text{ fm}$.

V_0 and r_0 are adjusted to reproduce nucleon separation energies and charge radii.

Woods-Saxon potential

Phenomenological WS potential

$$V(r) = V_0 f(r, R_0, a_0) + V_s \left(\frac{r_s}{\hbar} \right)^2 \frac{1}{r} \frac{d}{dr} [f(r, R_s, a_s)] (\mathbf{I} \cdot \boldsymbol{\sigma}) + V_{sym}(r) + V_C(r)$$

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Constraints:

- $a = 0.662 \pm 0.010$ fm; $R = r_0 (A - 1)^{1/3}$, $R_s = r_s (A - 1)^{1/3}$ with $r_s = 1.16$ fm.
- $R_C^2 = \frac{5}{3} \left[\langle r^2 \rangle_{ch} - \frac{3}{2} (a_p^2 - b^2/A) \right]$
- V_0 and r_0 are adjusted to reproduce experimental nucleon separation energies and charge radii.

Charge radii

Closure approximation and beyond

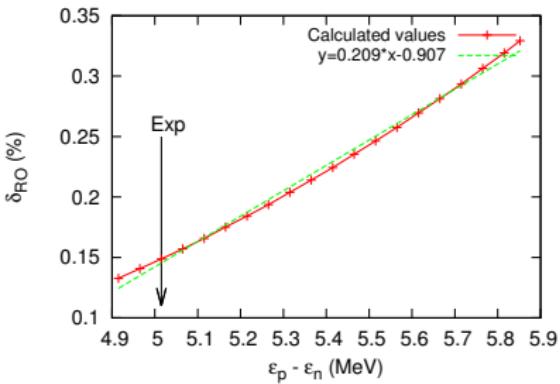
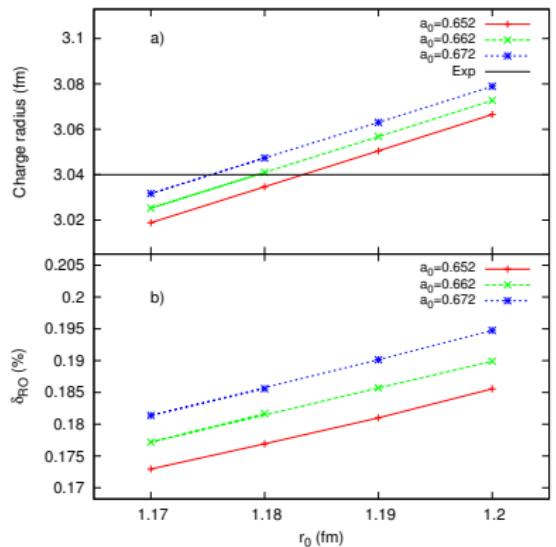
Without intermediate states (Towner, Hardy):

$$r_{ch}^2 = \frac{1}{Z} \sum_{\alpha} n(\alpha) \int_0^{\infty} |R_{\alpha}(r)|^2 r^4 dr$$

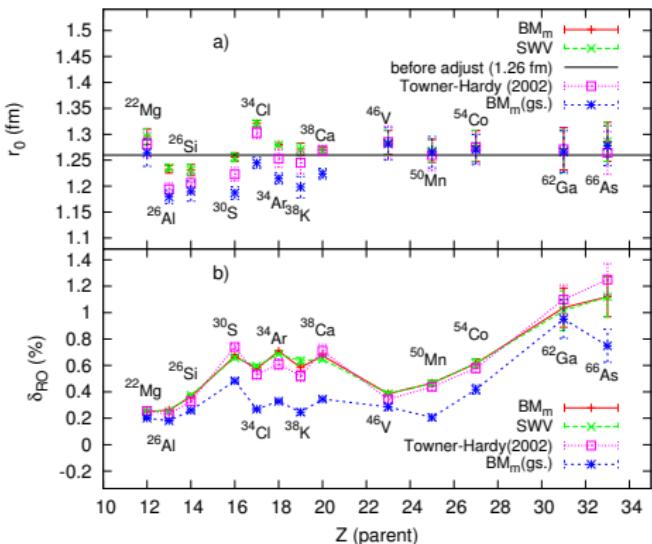
With intermediate states (present work):

$$r_{ch}^2 = \frac{1}{Z} \sum_{\alpha,\pi} S(i\pi k_{\alpha}) \int_0^{\infty} |R_{\alpha}^{\pi}(r)|^2 r^4 dr$$

Sensitivity to WS potential parameters: $^{26}\text{Al} \rightarrow ^{26}\text{Mg}$



Results δ_{RO} from adjustment of V_0



- δ_{RO} increases when intermediate states are taken into account.
- Dependence of parametrization is removed.
- Uncertainty on δ_{RO} comes mainly from the experimental uncertainty on the charge radii.

L. Xayavong, Ph.D. thesis, University of Bordeaux (2016).

Woods-Saxon potential with surface terms

Surface terms (Towner, Hardy)

$$V_g(r) = \frac{V_g \lambda_\pi^2}{a_s r} \exp\left(\frac{r - R_s}{a_s}\right) [f(r, R_s, a_s)]^2$$

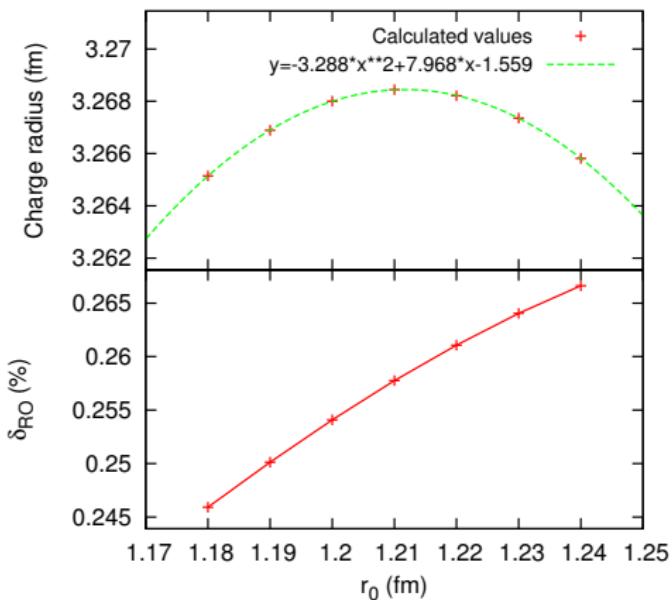
or

$$V_h(r) = V_h a_0^2 \left[\frac{d}{dr} f(r, R_0, a_0) \right]^2$$

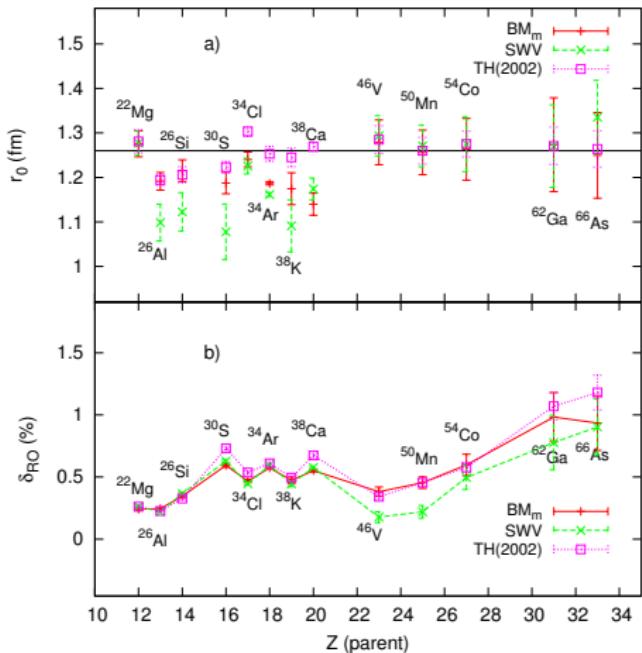
where $\lambda_\pi \approx 1.4$ fm

Constraints:

- V_g or V_h are adjusted instead of V_0 .
- $V_h(r)$ is rejected

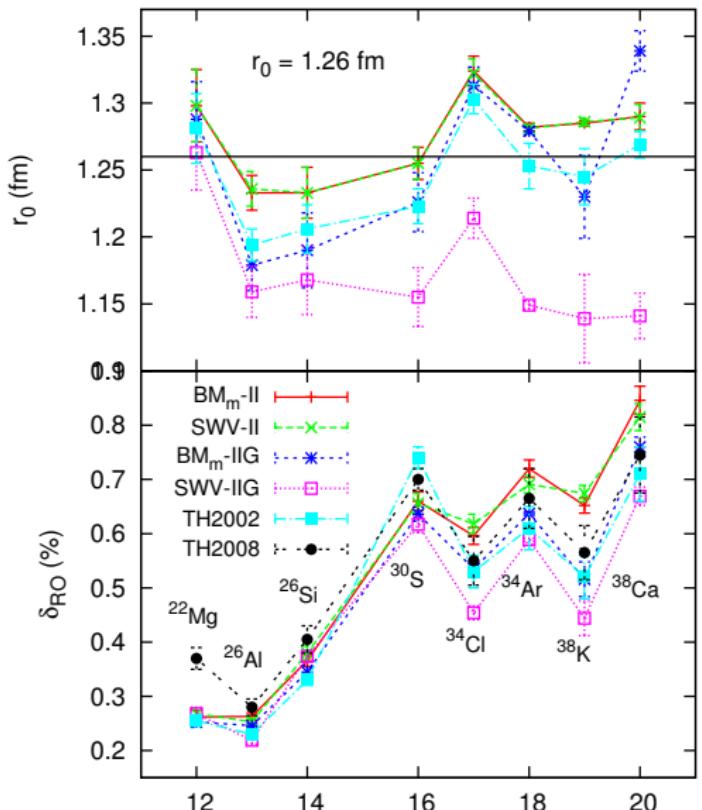


Results δ_{RO} from adjustment of V_g



- Dependence of parametrization is observed.
- TH2002: average from the fits with V_0 , V_g and V_h

Final results in *sd* shell



I.S. Towner, J.C. Hardy, PRC77
(2008)

Core orbitals

$$\delta_{RO} \approx \sum_{\pi^<, \alpha} S_\alpha^< \Omega_\alpha^< - \frac{1}{2} \sum_{\pi^>, \alpha} S_\alpha^> \Omega_\alpha^>$$

Guidance from experiment

Theoretical spectroscopic factors

$\mathcal{F}t$ values for 6 sd-shell emitters ($\nu = 5$): preliminary results

$$\chi^2/\nu = \frac{1}{N-1} \sum_{i=1}^N \frac{(\mathcal{F}t_i - \bar{\mathcal{F}t})^2}{\sigma_i^2}$$

Model	$\bar{\mathcal{F}t}$	χ^2/ν	CL
BM_m	3071.2(10)	2.84	1
SWV	3071.0(13)	3.93	0
BM_m -G	3072.90(70)	1.06	38
SWV-G	3074.49(80)	0.46	81
TH2002	3072.84(80)	1.92	9
TH2008	3072.26(90)	0.57	72

CVC test for δ_{RO} correction: preliminary results

I.S. Towner, J.C. Hardy, PRC82 (2010)

$$\delta_{RO}^{exp} = 1 + \delta_{NS} - \delta_{IM} - \frac{\overline{\mathcal{F}t}}{ft(1 + \delta'_R)}$$

$$\chi^2/\nu = \frac{1}{N-1} \sum_{i=1}^N \frac{(\delta_{RO}^{th}(i) - \delta_{RO}^{exp}(i))^2}{\sigma_{th}(i)^2 + \sigma_{exp}(i)^2}$$

Model	$\overline{\mathcal{F}t}$	χ^2/ν	CL
BM _m	3069.09	0.17	97
SWV	3068.45	0.19	97
BM _m -G	3071.82	0.25	94
SWV-G	3074.18	0.26	94
TH2002	3071.22	0.41	84
TH2008	3071.13	0.22	95

δ_{RO} from the shell model with Skyrme-HF wave functions

Skyrme parameterizations:

- SGII (*N. Van Giai, H. Sagawa, NPA371 (1981)*)
- SkM* (*J. Bartel et al, NPA386 (1982)*)
- Sly5 (*P. Chabanat et al, NPA635 (1998)*)

Spherical HF code Lenteur (*K. Bennaceur, IPN Lyon*).

Optimization

- Energy-dependent *local equivalent potential* (*C.B.Dover, N. Van Giai, NPA190 (1972)*):

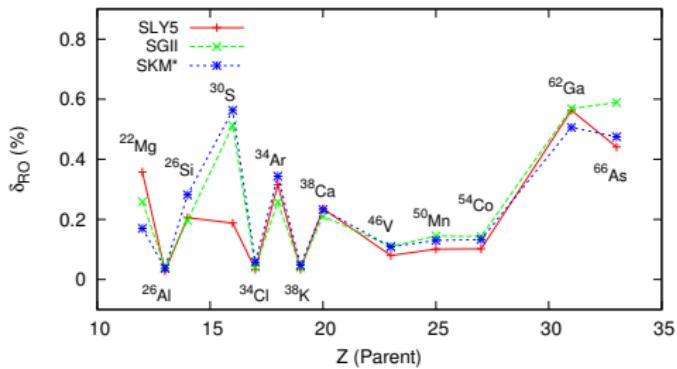
$$V^{LE}(r, \epsilon_\alpha) = V^0(r, \epsilon_\alpha) + V^{so}(r) \langle \vec{l} \cdot \vec{s} \rangle + V_C(r)$$

for

$$R_\alpha(r) = \sqrt{\frac{m^*(r)}{m}} R_\alpha^{LE}(r).$$

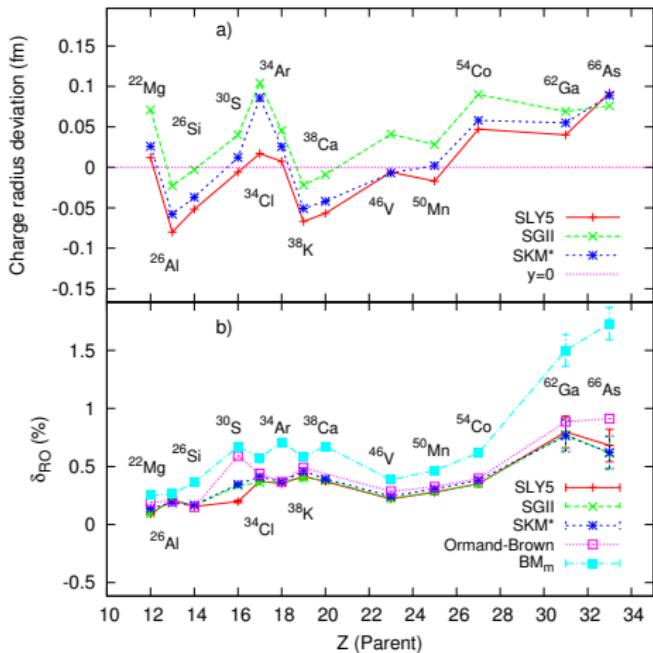
- Adjustment of the central term $V^0(r, \epsilon_\alpha)$ by a scaling factor.

δ_{RO} from the shell model with Skyrme-HF wave functions



- SGII (*N. Van Giai, H. Sagawa, NPA371 (1981)*)
- SkM* (*J. Bartel et al, NPA386 (1982)*)
- Sly5 (*P. Chabanat et al, NPA635 (1998)*)

HF potential adjusted



- δ_{RO} is consistent from different forces
- Opposite to WS staggering effect

L. Xayavong, N.S., M. Bender, K. Bennaceur, *Acta Phys. Pol. B10, 285 (2017)*.

HF potential: comments

- Test of the Slater approximation for the Coulomb term: **valid**
- Center-of-mass correction (two-body terms): **not important**
- Non-physical isospin symmetry breaking in $N \neq Z$ nuclei: **negligible**

Gogny-HF code Ghost, K. Bennaceur .

Summary and Perspectives

- New shell-model study of δ_C for some sd and pf shell $0^+ \rightarrow 0^+$ emitters.
- Under experimental constraints, the proposed procedure removes uncertainties due to different parameterizations. Results are consistent with previous studies.
- Open problems to be addressed :
 - Exact Fermi operator
 - Large model spaces
 - Inclusion of core orbitals
 - Extension of the studies to other experimentally important cases
- More work on the implementation of the HF wave functions.