Isospin-nonconserving shell-model for precision tests of electroweak theory

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Physics motivation

Isospin symmetry is broken in nuclear physics

- Coulomb force
- Charge-dependent nuclear forces

Experimental evidence on isospin-symmetry breaking

- Splittings of isobaric multiplets
- Isospin-forbidden processes (isospin-forbidden proton emission, Fermi β-decay to non-analogue states, $E1$-transitions in $N = Z$ nuclei, etc)

Accurate theoretical description of the isospin-symmetry breaking is crucial tests of fundamental symmetries underlying the Standard Model:

- superallowed $0^+ \to 0^+$ Fermi beta decay for test of CVC and, if holds, unitarity of the CKM matrix,
- asymmetry of mirror GT beta transitions for constraints on the induced tensor term in the axial-vector current,
- and other weak processes on nuclei.

Nuclear models to estimate isospin-symmetry breaking

- Shell model (from 60's . . ., I.S.Towner, J.C.Hardy, 1973 – 2013; W.E.Ormand, B.A.Brown, 1985 – 1995)
- No-core shell model (E.Caurier, P.Navratil et al, 2002)
- HF + Tamm-Dankoff or RPA (I.Hamamoto, H.Sagawa, J.Dobaczewski, T.Suzuki et al, 1993 – 1998)
- relativistic RPA approach (H.Liang, N.V.Giai, J.Meng, 2009)
- the angular-momentum-projected and isospin-projected HF model (W.Satula et al, 2009 – 2013)
- VAP technique on the HFB basis (A.Petrovici et al, 2008)
- Gamow shell-model (N.Michel et al, 2010)
- Isovector giant monopole resonance (N.Auerbach, 1983, 2009)
- Corrections to shell-model approach (G.A.Miller, A.Schwenk, 2008, 2009)

Present work: shell-model

- detailed information on individual nuclear states and transitions
- preserves fundamental symmetries of nuclei (rotational invariance, particle number conservation), allowing for an experimentally constrained calculation

Plan of the talk

1. Isospin-nonconserving shell-model (*sd* shell)
2. Applications:
   - Staggering of the IMME *b* and *c* coefficients
   - Validity of the quadratic form of the IMME
   - Isospin-forbidden proton emission
3. Nuclear structure corrections to superallowed $0^+ \to 0^+$ Fermi beta decay
4. Conclusions and outlook

1. Isospin-nonconserving shell-model

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

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

W.E. Ormand, B.A. Brown NPA491 (1989)

Y.H. Lam, Ph.D. thesis, CENBG (2011); Y.H. Lam, N.A.Smirnova, E. Caurier, PRC87 (2013).

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$$\hat{V}_{INC} = \lambda_C \hat{V}_C + \lambda_\pi \hat{V}_\pi + \lambda_\rho \hat{V}_\rho + \lambda_0 \hat{V}^{T=1} + \hat{H}_0^{IV}$$

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- Within perturbation theory:

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

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- The strength parameters are obtained in a 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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- Finally, we solve the eigenproblem for an isospin non-conserving Hamiltonian $[\hat{H}_{INC}, \hat{T}] \neq 0$:

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

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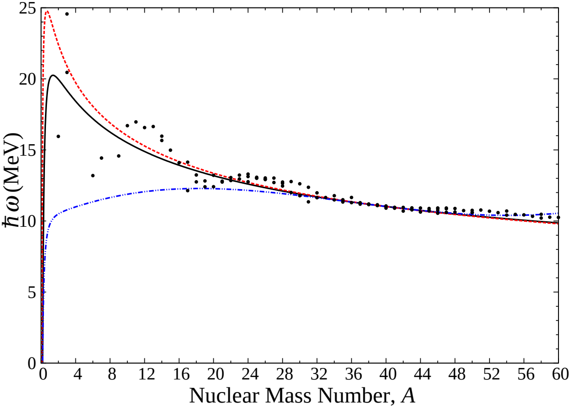
Y.H. Lam, Ph.D. thesis, CENBG (2011); Y.H. Lam, N.A.Smirnova, E. Caurier, PRC87 (2013).

Technical details: H.O. parameter



$$\hbar\omega(A) = 45A^{-1/3} - 25A^{-2/3}$$

Solid black line: *Blomqvist-Molinari, 1968*
Double-dot-dashed blue line: BM with correction factor from *Ormand, Brown, 1989*
Dashed red line: parametrization from *Kirson, 2007*

Our choice: hw deduced from exp. data on nuclear charge radii, *Angeli, 2004; Kirson, 2007*.

Technical details: SRCs

Jastrow-type: $$\int_0^\infty \phi'_{nl}(r)v(r)\phi'_{n'l}(r)r^2dr = \int_0^\infty \phi_{nl}(r)f(r)v(r)f(r)\phi_{n'l}(r)r^2dr \; .$$

with $f(r) = 1 - \gamma e^{-\alpha r^2}\left(1 - \beta r^2\right)$

Notation	α (fm^{-2})	β (fm^{-2})	γ	Ref.
MS	1.1	0.68	1.0	*G.A.Miller, J.E.Spencer, Ann. Phys. (NY) 100 (1976)*
CD-Bonn	1.52	1.88	0.46	*F.Šimkovic et al, PRC79 (2009)*
AV18	1.59	1.45	0.92	*F.Šimkovic et al, PRC79 (2009)*

UCOM: $$\int_0^\infty \phi_{n'l}(r)v\left(R_+(r)\right)\phi_{nl}(r)r^2dr$$

$$R_+^{\mathrm{I}}(r) = r + \alpha\left(\frac{r}{\beta}\right)^\eta \exp\left[-\exp\left(\frac{r}{\beta}\right)\right] \; ,$$

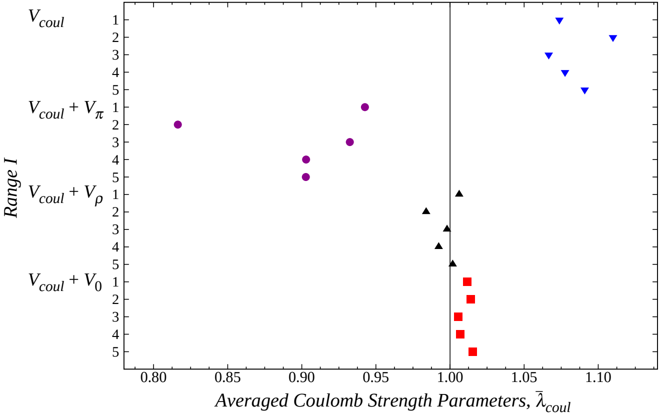
with $\alpha = 1.3793$ fm, $\beta = 0.8853$ fm, $\eta = 0.3724$ in the $S = 0$, $T = 1$ channel, and

$$R_+^{\mathrm{II}}(r) = r + \alpha\left(1 - \exp\left(-\frac{r}{\gamma}\right)\right)\exp\left[-\exp\left(\frac{r}{\beta}\right)\right] \; ,$$

with $\alpha = 0.5665$ fm, $\beta = 1.3888$ fm, $\gamma = 0.1786$ in the $S = 1$, $T = 1$ channel.

R.Roth et al, PRC72 (2005), M. Kortelainen et al, PLB647 (2007).

Coulomb strength parameters



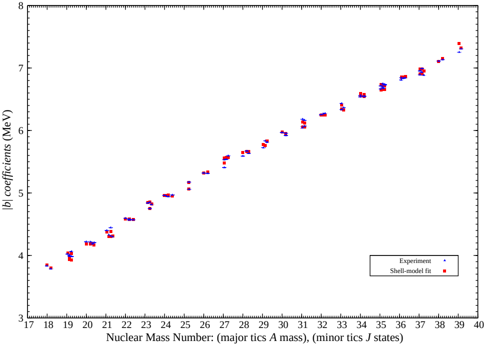
1– no SRC; 2 – Miller–Spencer, 3 – CD-Bonn, 4 – AV18; 5 – UCOM.

$\lambda^{(1)} \sim$ 1–1.8%, $\lambda^{(2)} \sim$3–4.2%.

Results of the fit to *b* coefficients in *sd*-shell

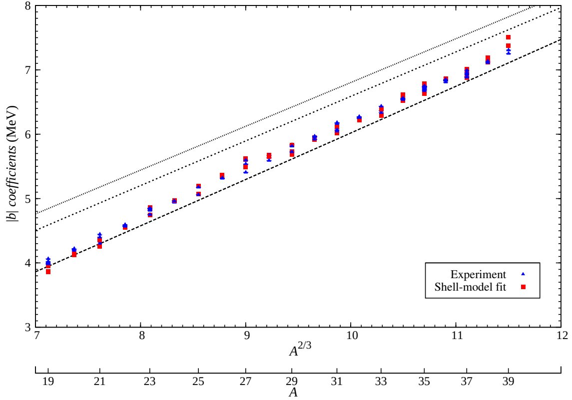
$$M(\alpha, T, T_z) = a(\alpha, T) + b(\alpha, T)T_z + c(\alpha, T)T_z^2$$

USD (*Brown, Wildenthal, 1988*) or USDA/USDB (*Brown, Richter, 2006*) plus the INC term ($\hat{V}_C$, $\hat{V}_\rho$ 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 $\approx$ 32 keV
- experimental IMME database: Lam, Blank, Smirnova, Antony, Bueb, ADNDT (2013) – in press.

Results of the fit to *b* coefficients in *sd*-shell



Dotted-dashed line: $|b| = \frac{3e^2(A-1)}{5r_0 A^{1/3}}$,

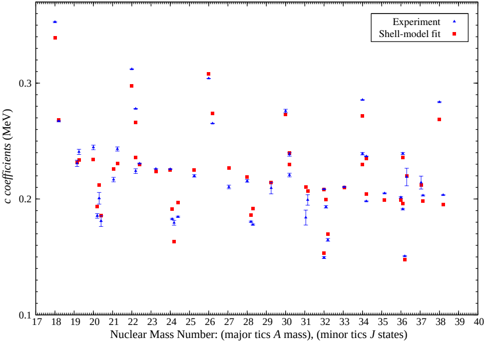
double-dotted-dashed line is $|b| = \frac{3e^2}{5r_0} A^{2/3}$,

dashed line: *b* from the model of *Möller, Nix, ADNDT39 (1988)*

Results of the fit to c coefficients in sd-shell

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

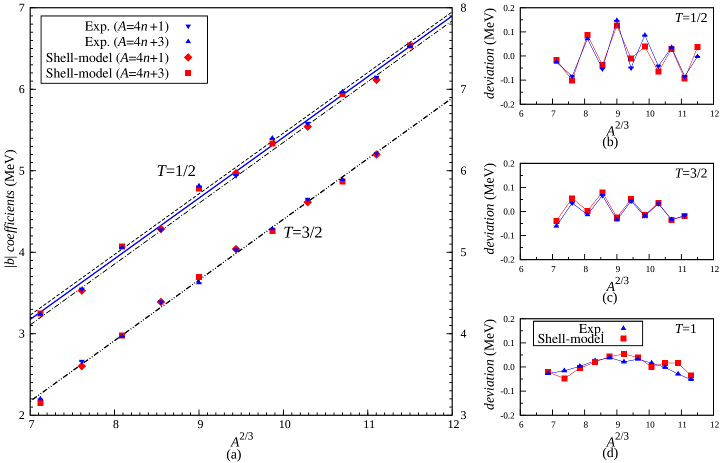
USD (*Brown, Wildenthal, 1988*) or USDA/USDB (*Brown, Richter, 2006*) plus the INC term ($\hat{V}_C$ and $\hat{V}_\rho$ or $\hat{V}^{T=1}$)



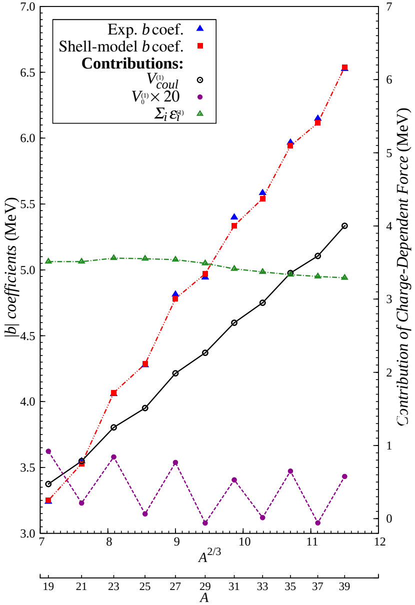
- c coefficients ($v_{pp} + v_{nn} - 2v_{pn}$); 51 data points ($T = 1, 3/2, 2$);
- rms $\approx$ 10 keV

2A. Staggering of *b*-coefficients of *sd*-shell nuclei

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



Contributions of various INC terms to b coefficients



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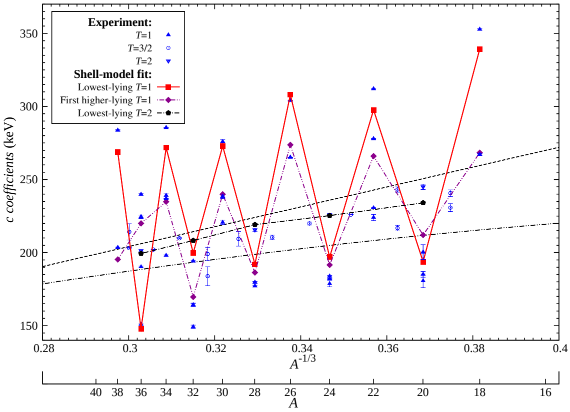
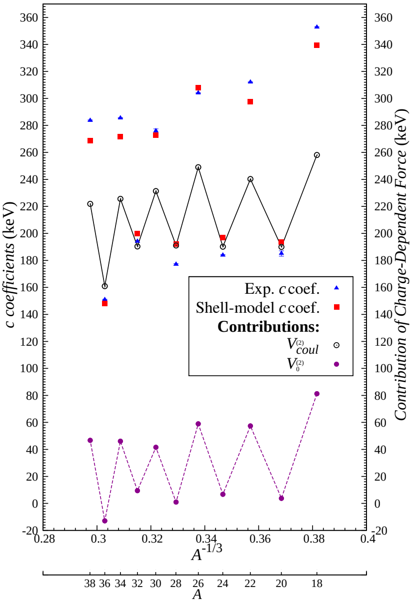


Black dashed line: $c = \frac{3e^2}{5r_0} A^{-1/3}$,

Double-dot-dashed line: c from the model of *Möller, Nix, ADNDT39 (1988)*

Contributions of various INC terms to c coefficients



B. IMME beyond a quadratic form

Quadratic IMME has been deduced at first order in perturbation theory. Higher-order terms in T_z may be present due to

- isospin-symmetry breaking three-body (or four-body) interactions;
- Coulomb effects at second order in perturbation theory (isospin mixing);
- Thomas-Ehrman shift in nuclei with loosely-bound low-l orbitals.

$$M(\alpha, T, T_z) = a(\alpha, T) + b(\alpha, T)T_z + c(\alpha, T)T_z^2 + d(\alpha, T)T_z^3 + e(\alpha, T)T_z^4$$

Theoretical estimations of $d \sim 1$ keV.
E.M. Henley, C.E. Lacy (1969); J. Jänecke (1969); G.F. Bertsch, S. Kahana (1970)

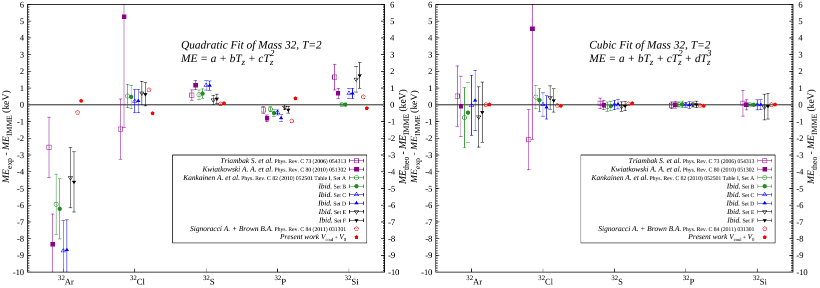
$J^\pi = 0^+$ quintet ($T = 2$) in $A = 32$ isobars

Nuclide	Mass excess (keV)	References
^{32}Ar	-2200.4 (18)	K. Blaum et al (2003)
^{32}Cl	-8288.8 (10)	C. Wrede et al (2010); A. Kankainen et al (2010)
^{32}S	-13967.57 (28)	W. Shi et al (2005); S. Triambak et al (2006)
^{32}P	-19232.46 (15) -19232.78 (20)	M. Redshow et al (2008) AME03, P.M. Endt (1998)
^{32}Si	-24080.86 (77) -24080.92 (5) -24077.69 (30)	A. Paul et al (2001) M. Redshow et al (2008) A.A. Kwiatkowski et al (2009)

Experimental and theoretical d coefficients for the 0^+ quintet in $A = 32$

	$\chi^2/n_{\text{quadr.}}$	χ^2/n_{cubic}	d (keV)
S. Triambak et al (2006)	6.5	0.77	0.54 (16)
A. Kwiatkowski et al (2009)	30.6	0.48	1.00 (9)
Set A from A. Kankainen et al (2010)	9.9	0.86	0.52 (12)
Set B *Ibid.*	12.3	0.31	0.60 (13)
Set C *Ibid.*	28.3	0.002	0.90 (12)
Set D *Ibid.*	30.8	0.09	1.00 (13)
Set E *Ibid.*	6.5	0.74	0.51 (15)
Set F *Ibid.*	8.3	0.28	0.62 (16)
A. Signoracci, B.A. Brown (2011)	1.09	0.005	0.39
Present work (2013)	0.26	0.02	-0.19

IMME beyond the quadratic form in the $A = 32$ quintet



Isospin-mixing leads to breaking of the quadratic IMME.

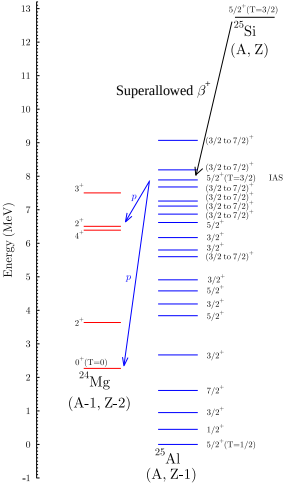
A. Signoracci, B.A.Brown, PRC84 (2011).

Y.H. Lam, N. Smirnova, E. Caurier, PRC87 (2013)

Comparison of b, c, d, and e coefficients for the 0^+ quintet in $A = 32$

		b, c (keV)	b, c, d (keV)	b, c, e (keV)	b, c, d, e (keV)
Experiment	b	-5471.85 (27)	-5472.83 (29)	-5470.45 (29)	-5472.64 (68)
	c	208.55 (14)	207.12 (23)	204.92 (23)	206.89 (75)
	d	—	0.89 (11)	—	0.83 (22)
	e	—	—	0.69 (11)	0.06 (19)
	χ^2/n	32.15	0.10	13.80	
Signoracci, Brown (2011)	b	-5417.7	-5419.0	-5417.7	-5419.0
	c	209.1	209.1	209.0	209.0
	d	—	0.39	—	0.39
	e	—	—	0.03	0.03
	χ^2/n	1.09	0.006	2.17	—
Present work	b	-5464.4	-5463.8	-5464.4	-5463.8
	c	207.6	207.6	207.4	207.4
	d	—	-0.19	—	-0.19
	e	—	—	0.045	0.045
	χ^2/n	0.26	0.017	0.50	—

C. Beta-delayed proton emission from ^{25}Si



IAS

Beta-delayed proton emission from ^{25}Si

Present results: from USD interaction and INC term. θ_l^2 are spectroscopic factors, Γ_p are proton widths, $\Gamma_p = 2\sum_l \theta_l^2 \gamma^2 P_l(Q_p)$

^{24}Mg	E_{exc} (MeV)		$E_{c.m.}$	$10^4\theta^2$		Γ_p (keV)	Branching ratios (%)	
J^π	E_{exp}	E_{theo}	(MeV)	$l=0$	$l=2$		Theory	Exp
0^+	0.000	0.000 (0)	5.624 (3)	0.00 (0)	0.059 (4)	11 (1)	10.0 (5)	18.60
2_1^+	1.369	1.495 (1)	4.252 (2)	0.04 (1)	0.82 (6)	94 (12)	83.0 (15)	74.40
4_1^+	4.123	4.347 (4)	1.489 (7)	0.00 (0)	0.09 (1)	0.07 (1)	0.06 (0)	3.74
2_2^+	4.238	4.116 (5)	1.377 (6)	0.23 (2)	0.033 (4)	7.6 (6)	6.9 (1)	3.20
3_1^+	5.235	5.060 (5)	0.389 (5)	0.09 (1)	0.27 (3)	0.0 (0)	0.0 (0)	—

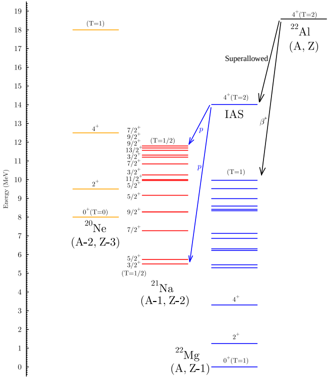
Experiment: *J.-C. Thomas et al, Eur. Phys. J.* **A21**, *419 (2006)*

Theory: *Y.H.Lam, N.A.Smirnova, E.Caurier, proc. of INPC2013, Firenze, June 2–7 (2013)*

Beta-delayed proton emission from ^{22}Al

Experimental study of
βp emission from ^{22}Al:

- *M.D. Cable et al (1982)*
  $4^+(IAS) \rightarrow 3/2^+_{gs}, 5/2^+_1$
- *B. Blank et al (1997)*
  $4^+(IAS) \rightarrow 7/2^+_1$
- *N.L. Achouri et al (2006)*
  $4^+(IAS) \rightarrow 7/2^+_1, 9/2^+_1$



Present results: from USD interaction and INC term.
θ_l^2 are spectroscopic factors, Γ_p are proton widths, $\Gamma_p = 2\sum_l \theta_l^2 \gamma^2 P_l(Q_p)$

^{21}Na	E^{th}_{exc}	Present work				B.A. Brown, PRL65 (1990)			
	(MeV)	$10^4\theta_l^2$		Γ_p	BR	$10^4\theta_l^2$		Γ_p	BR
		$l=0$	$l=2$	(keV)	(%)	$l=0$	$l=2$	(keV)	(%)
$3/2^+$	0.0		0.090(2)	0.04(0)	1.6(0)		0.13	0.055	5.3
$5/2^+$	0.236		0.267(4)	0.11(0)	4.3(1)		0.18	0.071	6.9
$7/2^+$	1.779	0.009(4)	4.73(21)	1.21(6)	45.7(22)	0.04	1.71	0.412	40.0
$9/2^+$	2.780	0.006(0)	2.54(23)	0.38(4)	15.4(14)	0.09	0.56	0.144	14.0
$5/2^+$	3.694		0.28(7)	0.02(1)	1.0(2)		0.24	0.017	1.6
$11/2^+$	4.428		1.91(30)	0.09(1)	3.7(6)		1.22	0.041	4.0
$5/2^+$	4.556		0.37(5)	0.02(0)	0.6(1)		1.34	0.043	4.1
$3/2^+$	4.785		0.25(2)	0.01(0)	0.3(0)		0.49	0.012	1.1
$7/2^+$	5.328	0.184(4)	0.72(17)	0.08(1)	3.3(2)	0.00	0.11	0.001	0.1
$3/2^+$	5.784		0.10(0)	0.00(0)	0.0(0)		0.07	0.000	0.0
$9/2^+$	6.078	0.90(5)	0.17(2)	0.18(1)	7.1(4)	0.10	0.07	0.008	0.8
$13/2^+$	6.141		0.54(3)	0.00(0)	0.1(0)		0.78	0.004	0.4
$9/2^+$	6.192	1.05(3)	6.9(2)	0.21(1)	8.5(2)	2.29	5.69	0.169	16.5
$7/2^+$	6.274	1.02(7)	14.2(4)	0.21(1)	8.4(5)	0.40	11.90	0.043	4.1

Remark: USDA interaction produces strong mixing for the 4^+ ($T=2$ IAS) in ^{22}Mg.

Present work: *N.A.Smirnova, Y.H.Lam, E.Caurier, Acta Phys. Pol. B44 (2013)*

3. Isospin-symmetry breaking correction δ_C to superallowed $0^+ \to 0^+$ beta decay

$$Ft^{0^+\to 0^+} \equiv ft^{0^+\to 0^+}(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{|M_{F0}|^2 G_V^2 (1+\Delta_R)}$$

where, δ_R', δ_{NS}, Δ_R are radiative corrections, δ_C is a nuclear structure correction.
Test of CVC and the value of $|V_{ud}| = G_V/G_V^{\mu}$.

Within the shell model (approach of Towner, Hardy and Ormand, Brown),

$$M_F = \sum_{\alpha,\beta} \langle f|a_\alpha^+ a_\beta|i\rangle \langle \alpha|\tau_+|\beta\rangle$$

$$\langle \alpha|\tau_+|\beta\rangle = \delta_{\alpha,\beta} \int_0^\infty R_\alpha^n(r) R_\beta^p(r) r^2 dr = \delta_{\alpha,\beta} r_\alpha$$

Deficiency of this operator: *G.A.Miller, A.Schwenk, PRC78, 2008 and PRC80, 2009*

$$M_F = \langle f|\tau_+|i\rangle = \sum_{\alpha,\pi} \langle f|a_\alpha^+|\pi\rangle\langle \pi|a_\alpha|i\rangle r_\alpha^\pi$$

$$M_0 = \sum_{\alpha,\pi} |\langle f|a_\alpha^+|\pi\rangle|^2 = \sqrt{T(T+1) - T_{zi}T_{zf}}$$

$$|M_F|^2 = |M_0|^2(1-\delta_C), \quad \text{where} \quad \delta_C = \delta_{IM} + \delta_{RO}$$

Isospin-mixing correction (δ_{IM})

$$M_F = M_0 \left[1 - \frac{1}{M_0}\left(M_0 - \sum_{\alpha,\pi}\langle f|a_\alpha^+|\pi\rangle\langle\pi|a_\alpha|i\rangle\right) - \frac{1}{M_0}\sum_{\alpha,\pi}|\langle f|a_\alpha^+|\pi\rangle|^2(1-r_\alpha^\pi)\right]$$

$$\delta_{IM} \simeq 2\left(1 - \frac{1}{M_0}\sum_{\alpha,\pi}\langle f|a_\alpha^+|\pi\rangle\langle\pi|a_\alpha|i\rangle\right)$$

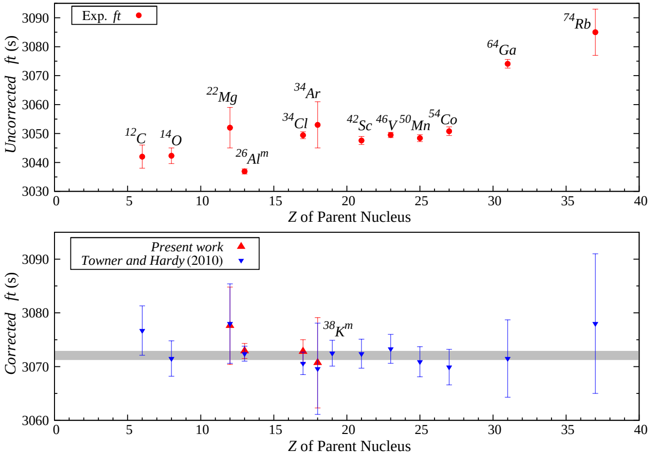
$$\delta_{RO} \simeq \frac{2}{M_0}\sum_{\alpha,\pi}|\langle f|a_\alpha^+|\pi\rangle|^2(1-r_\alpha^\pi)$$

Present results: USD interaction plus V_{INC}

	δ_{IM} (%)			Ft	
Emitter	Present work (2013)	Ormand, Brown (1989)	Towner, Hardy (2008)	Present work (2013)	Towner, Hardy (2010)
^{22}Mg	0.022(1)	0.017	0.010 (10)	3077.6(72)	3077.6(74)
^{26m}Al	0.012(1)	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	0.036(1)	0.06	0.091 (10)	3072.6(21)	3070.6(21)
^{34}Ar	0.006(1)	0.008	0.023 (10)	3070.7(84)	3069.6(85)

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

From Towner, Hardy, Rep. Prog. Phys. 73 (2010); Y.H. Lam, N. Smirnova, E. Caurier, PRC87 (2013)



Radial overlap correction

WS wave functions

$$V(r) = -V_{ws} f(r) - V_{so} \frac{r_0^2}{r} \frac{d}{dr}[f(r)] \mathbf{l} \cdot \mathbf{s} + V_c h(r)$$

$$f(r) = \frac{1}{\left[1+\exp\left(\frac{r-R_0}{a}\right)\right]}$$

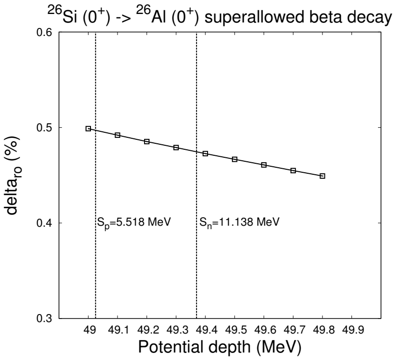
$$h(r) = \begin{cases} \frac{1}{r} & \text{for} \quad r \geq R_0 \\ \frac{1}{2R_0}\left(3 - \frac{r^2}{R_0^2}\right) & \text{for} \quad r < R_0 \end{cases}$$

$R_0 = r_0(A-1)^{1/3}$, $V_c = Ze^2$, $r_0 = 1.27$ fm, $a = 0.75$ fm,
$V_{ws} = V_0 - V_{NZ} * (N-Z)t_z/A$, $V_{so} = V_{ls} * V_{ws}$,
$V_0 = 50.5$ MeV, $V_{NZ} = 32$ MeV, $V_{ls} = 0.22$
(Bohr-Mottelson parametrization).

Adjustment: to reproduce nucleon separation energies

Radial overlap correction

$$R(r) \sim \exp\left(-\frac{\sqrt{2m|E|}}{\hbar}r\right)$$



Radial overlap correction δ_{RO}: preliminary results

Radial overlap correction from Woods-Saxon potential

	δ_{RO} (%)		
Emitter	Present work (2013)	Ormand, Brown (1985)	Towner, Hardy (2008)
^{22}Mg	0.238(3)	0.425	0.370 (30)
^{26m}Al	0.398(1)	0.229	0.280 (15)
^{26}Si	0.483(14)	0.486	0.405 (25)
^{30}S	0.756(20)	1.058	0.700 (20)
^{34}Cl	0.352(5)	0.561	0.550 (45)
^{34}Ar	0.408(5)	0.732	0.635 (55)

Summary and Outlook

- We constructed a very precise **INC shell-model Hamiltonian** in *sd* shell with a large potential of applications.
- The INC Hamiltonian accurately describes the **staggering** of the IMME *b* and *c* coefficients with mass numbers.
- The INC Hamiltonian allows to study the **validity of the quadratic IMME** in quartets and quintets.
- **Isospin-forbidden nucleon emission** branching ratios (like in ^{22}Al) are very sensitive to the detailed structure of the INC potential.
- Fermi beta decay to non-analogue 0^+ states (for heavier nuclei, from ^{38}K): $|M_F^n|^2 = 2\delta_{IM}^n$ (*E. Hagberg et al, PRL73, 1984*)).
- Isospin-forbidden Fermi beta decay ($J^\pi \to J^\pi$, $J \neq 0$)

Outlook

- Improvements in the fitting algorithm.
- Extension to *psd*, *sdpf* and *pf* shell nuclei is in progress.
- Careful study of WS and further HF spherical wave functions for δ_{RO}.
- Experimental information on proton-rich nuclei with $N \sim Z$ (displacement of energy levels in mirror nuclei, Q-values, lifetimes, branching ratios, spectroscopic factors and partial widths isospin-forbidden particle emission, isospin-forbidden Fermi decay, ...) is important to constrain the model.