Interplay of Nuclear Physics and Precision Tests of the Standard Model

Misha Gorshteyn

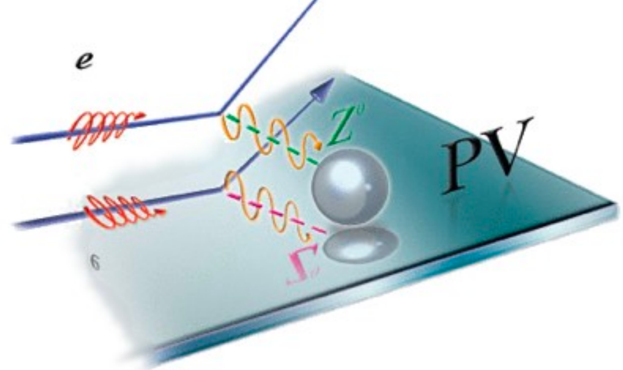
Virtual MITP Workshop “Parity Violation and Related Subjects” — July 27, 2020

Outline

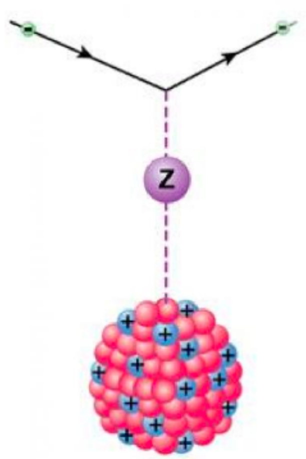
- Precision tests of the SM and beyond with nuclei: This Workshop & Global Context
- V_{ud}, CKM unitarity and nuclear structure
- Neutron skins as a signal of ISB effects: sub-% measurement of weak radii of selected daughter nuclei as an independent constraint on δ_C

Precision tests of the weak sector of SM

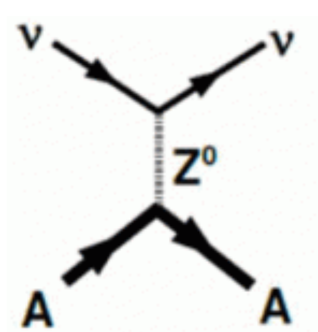
PV Electron Scattering
Elastic & Inelastic



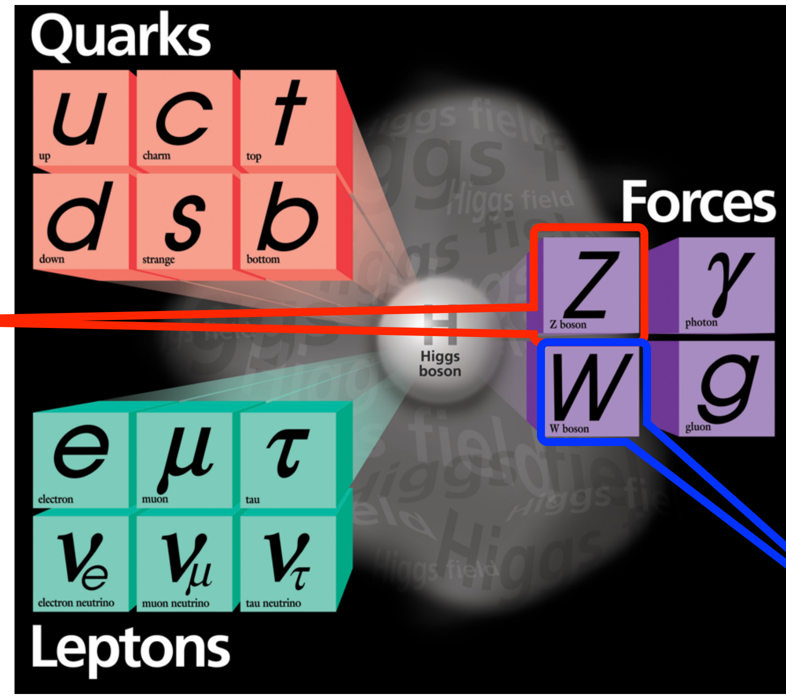
PV in Atoms



Coherent ν-Nucleus Scattering



Covered in this workshop



Objects of interest:

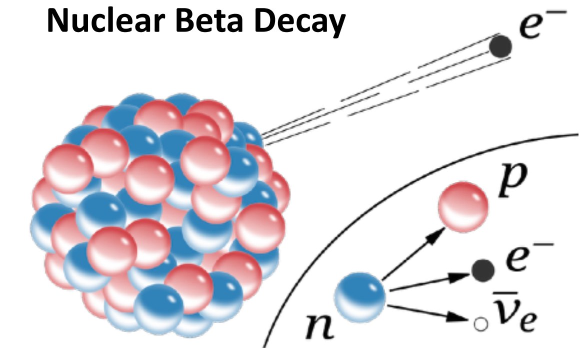
Bare SM Lagrangian parameters
- Couplings
- Mixing angles
- Neutrino masses

Radiative Corrections

Specific for semileptonic processes:

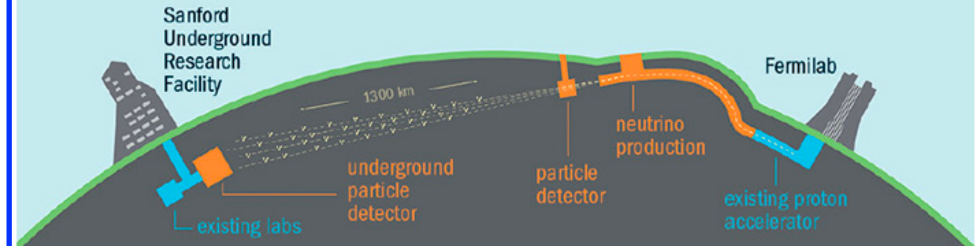
Effects of strong interaction on top of the lepton-quark interaction

Nuclear Beta Decay

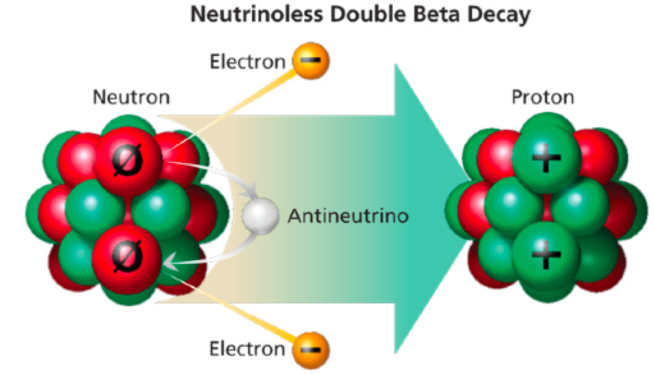


Connection to PVES
Addressed in this talk

Neutrino Oscillation Parameters



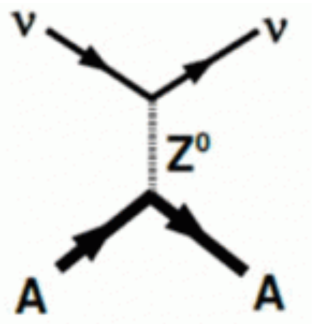
Neutrinoless Double Beta Decay



Not covered in this workshop
But define a broader context

Precision tests at this workshop

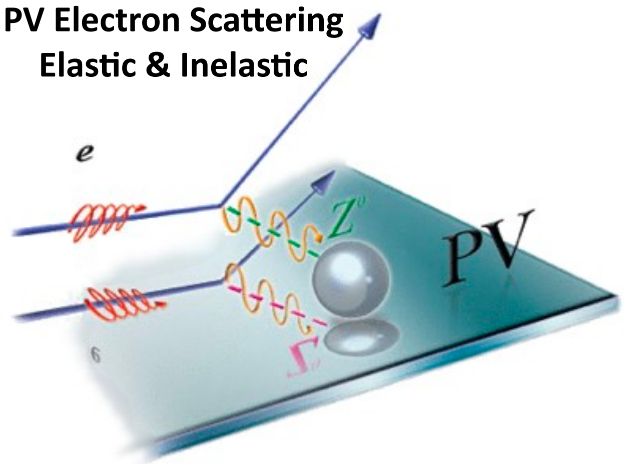
Coherent ν-Nucleus Scattering



July 27
Monday

Kate Scholberg — CEvNS Experiments
Baha Balantekin — Theory of (B)SM for CEvNS
Sonia Bacca — CEvNS on Ar-40 from first principles

PV Electron Scattering
Elastic & Inelastic



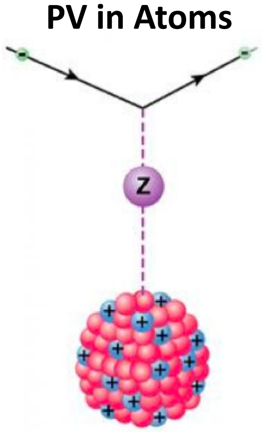
July 28
Tuesday

Ayres Freitas — SM radiative corrections to PVES
David Armstrong — Qweak beyond the proton's weak charge
Paul Souder — MOLLER, SOLID, P2
Hubert Spiesberger — EW physics at LHeC

July 29
Wednesday

Jorge Piekarewicz — PREX (II) in the multimessenger era
Juliette Mammei — Meet the REXes
Dustin McNulty — Beam normal spin asymmetry from REXes
Sasha Koshchii — Weak charge & radius of C-12 at P2

PV in Atoms



July 30
Thursday

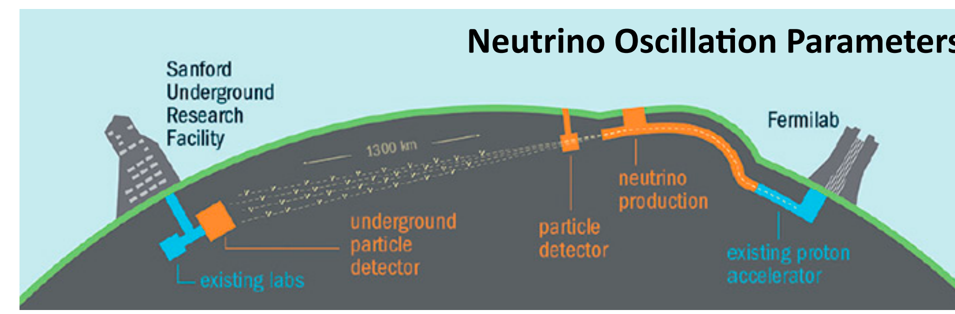
Witek Krasny — Tertiary $\nu(\bar{\nu})$ beams at Gamma Factory@CERN
Concettina Sfienti — Nuclear EOS studies in the Laboratory
Dionysis Antipas — R_{n-p} and anapole moment in Yb atoms
Andrei Derevianko — Atomic PV: Quo Vadis?

Postponed to the presence workshop
“Precision Tests with NC coherent interactions with nuclei”
June 7-11, 2021

Neutrino oscillation experiments

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{2E_\nu} \right)$$

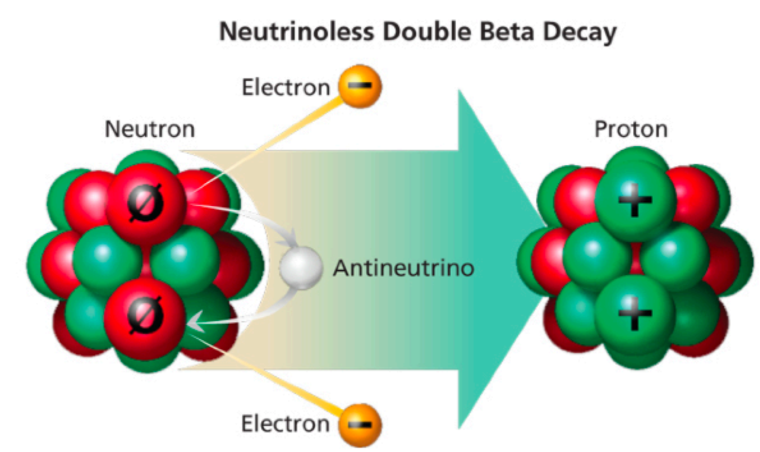
Neutrino interactions in the nuclear/hadronic energy range used for energy reconstruction



Neutrinoless double-beta decay — if neutrinos are Majorana

$$T_{1/2}^{0\nu\beta\beta} = (G|M|^2 \langle m_{\beta\beta} \rangle^2)^{-1} \sim 10^{27-28} \left(\frac{0.01\, eV}{\langle m_{\beta\beta} \rangle} \right)^2 y$$

$$\langle m_{\beta\beta} \rangle = | \sum_i U_{ei}^2 m_i |$$

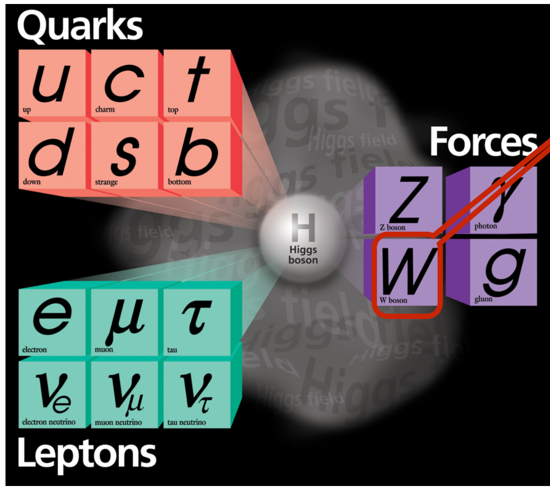


Nuclear matrix element M — central ingredient for predicting rates

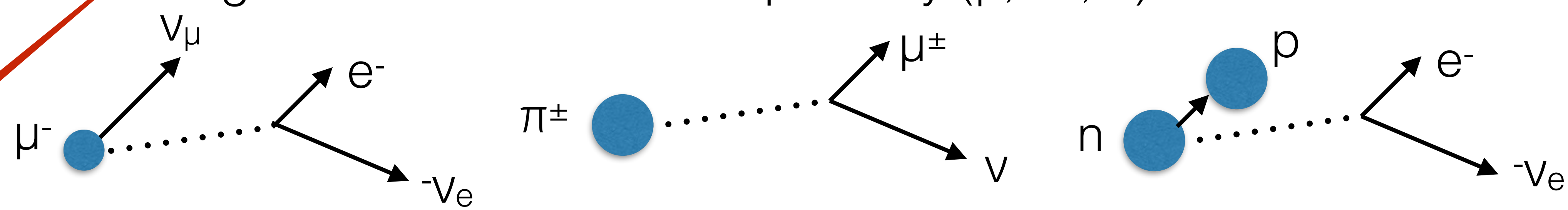
All the more reasons to meet again next year in Mainz in person (hopefully)

Precision tests of SM with charged weak current: V_{ud}, CKM unitarity and nuclear structure

Precise beta decays: universality of weak interaction



Charged current interaction - β-decay (μ, π±, n)



Rates close but not the same: CKM mixing matrix + Radiative Corrections
Crucial ingredients for establishing the Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

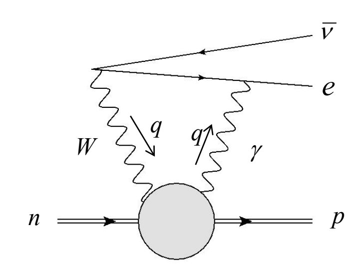
CKM - Determines the relative strength of the weak CC interaction of quarks vs. that of leptons

CKM unitarity - measure of completeness of the SM: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

PDG2020: CKM unitarity in the top row $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(3)_{V_{ud}}(4)_{V_{us}}$ **— 3σ deficit**

PDG 2018: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(4)_{V_{ud}}(2)_{V_{us}}$

Main reason: re-evaluation of radiative corrections
Application of dispersion theory to γW-box
Use of neutrino data (purely theoretical before)
Uncertainty ~halved but central value shifted



C-Y Seng et al., Phys.Rev.Lett. 121 (2018) 24, 241804
C-Y Seng, MG, M.J. Ramsey-Musolf, Phys.Rev. D 100 (2019) 1, 013001
MG, Phys.Rev.Lett. 123 (2019) 4, 042503
C-Y Seng, X. Feng, MG, L-C Jin, Phys.Rev. D 101 (2020) 11, 111301
A. Czarnecki, B. Marciano, A. Sirlin, Phys.Rev. D 100 (2019) 7, 073008

Status of V_{ud}

0+-0+ nuclear decays $|V_{ud}|^2 = \frac{2984.43s}{\mathcal{F}t(1+\Delta_R^V)}$ $|V_{ud}^{0^+-0^+}| = 0.9737\,(1)_{exp,\,nucl}\,(1)_{RCn}$

Free neutron decay $|V_{ud}|^2 = \frac{5024.7\text{ s}}{\tau_n(1+3g_A{}^2)(1+\Delta_R)}$ $|V_{ud}^{\text{free n}}| = 0.9733\,(3)_{\tau_n}\,(3)_{g_A}\,(1)_{RCn}$

Pion decay $\pi^+ \to \pi^0 e^+ \nu_e$ $|V_{ud}|^2 = \frac{0.9799}{(1+\delta)} \frac{\Gamma_{\pi\ell 3}}{0.3988(23)\,\text{s}^{-1}}$ $|V_{ud}^{\pi\ell 3}| = 0.9739\,(27)_{exp}\,(1)_{RC\pi}$

Major reduction of uncertainties in the past 2 years:

$\Delta_R^V = 0.02467(22)$ DR + Exp + Lattice: Factor 2

C-Y Seng et al., Phys.Rev.Lett. 121 (2018) 24, 241804;
C-Y Seng, MG, M.J. Ramsey-Musolf, Phys.Rev. D 100 (2019) 1, 013001;
MG, Phys.Rev.Lett. 123 (2019) 4, 042503;
C-Y Seng, X. Feng, MG, L-C Jin, Phys.Rev. D 101 (2020) 11, 111301;
A. Czarnecki, B. Marciano, A. Sirlin, Phys.Rev. D 100 (2019) 7, 073008

$g_A = -1.27641(56)$ Exp.: Factor 4

B. Märkisch et al [PERKEO-III], Phys.Rev.Lett. 122 (2019) 24, 242501

$\delta = 0.0332(3)$ Lattice: Factor 3

X. Feng, MG, L-C Jin, P-X Ma, C-Y Seng, Phys.Rev.Lett. 124 (2020) 19, 192002

Main contributor to top-row CKM unitarity constraint — V_{ud}

Value dominated by nuclear $0^+ - 0^+$ decays — prone to nuclear effects

Nuclear corrections — (almost) purely theoretical — room for major contribution

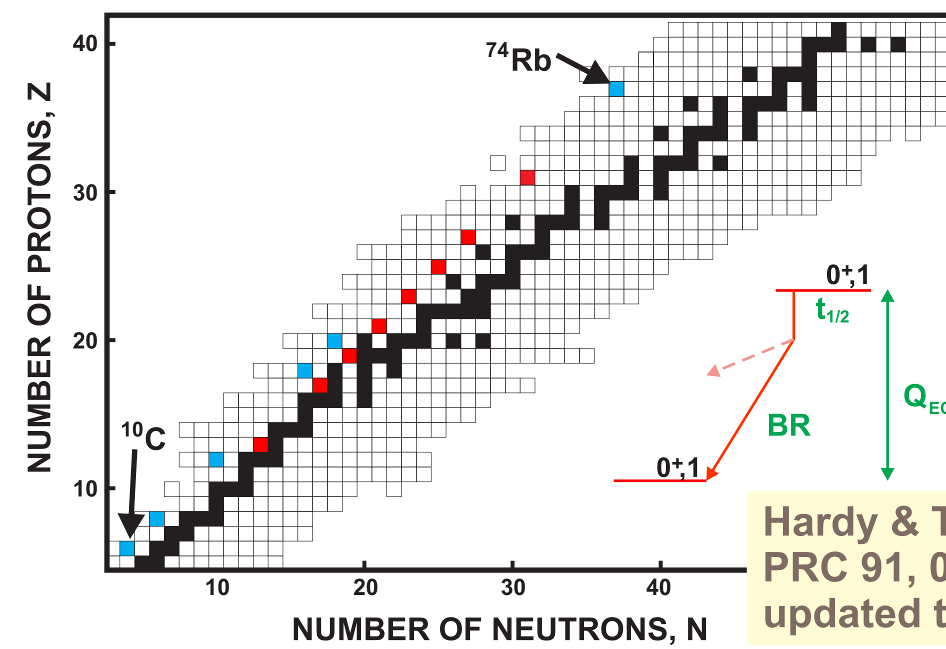
Why are superallowed decays special?

Superallowed 0^+-0^+ nuclear decays:

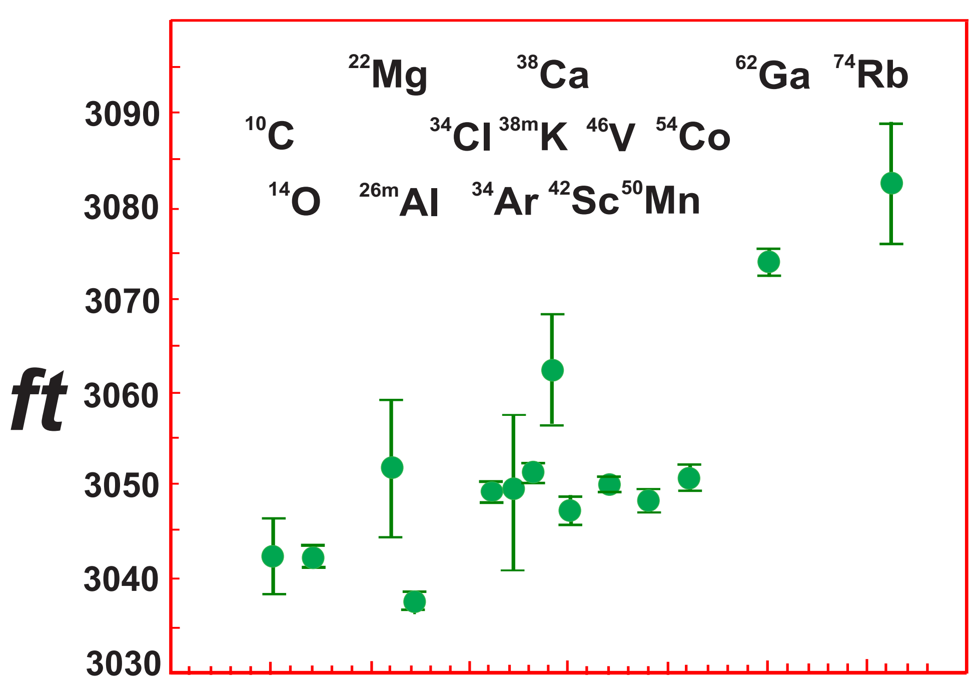
- only conserved vector current (unlike the neutron decay and other mirror decays)
- many decays (unlike pion decay)
- all decay rates should be the same modulo phase space

Experiment: **f** - phase space (Q value) and **t** - partial half-life ($t_{1/2}$, branching ratio)

- **8 cases with *ft*-values measured to <0.05% precision; 6 more cases with 0.05-0.3% precision.**
- **~220 individual measurements with compatible precision**



Hardy & Towner
PRC 91, 025501 (2015)
updated to 2017



ft values: same within ~2% but not exactly!

Reason: SU(2) slightly broken

a. QED RC depends on nuclear charge
b. Nuclear WF are not SU(2) symmetric

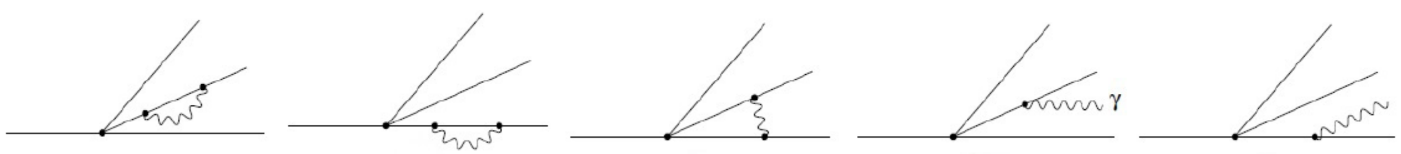
Why are superallowed decays special?

$$|V_{ud}|^2 = \frac{2984.432(3)}{\mathcal{F}t(1+\Delta_R^V)}$$

Modified ft-values to include these effects

$$\mathscr{F}t = ft(1+\delta_R')(1-\delta_C+\delta_{NS})$$

δ'_R - "outer" correction (depends on e-energy) - QED

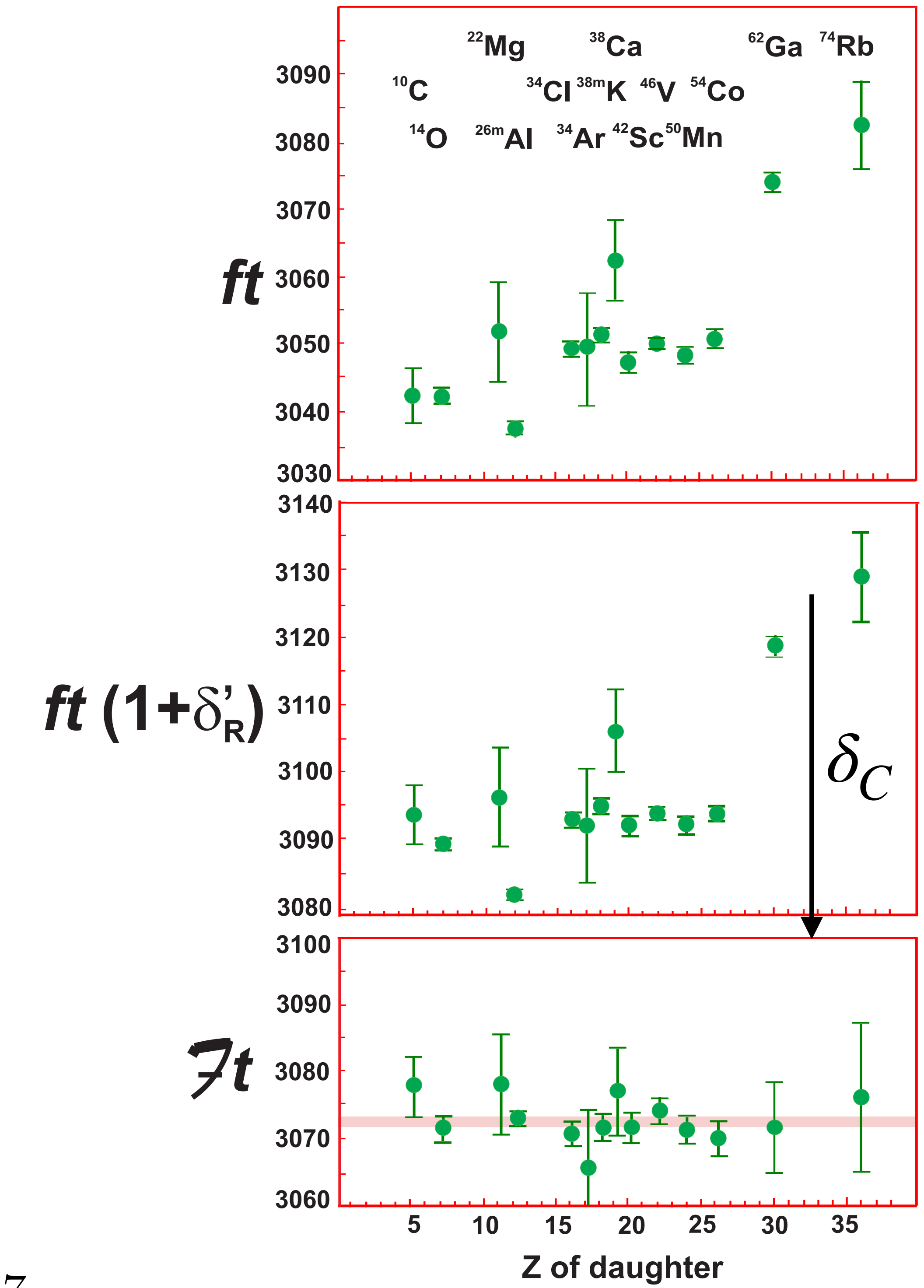


δ_C - SU(2) breaking in the nuclear matrix elements

- mismatch of radial WF in parent-daughter
- mixing of different isospin states

δ_{NS} - RC (γW-box) depending on the nuclear structure

δ_C, δ_{NS} - energy independent



Average

$$\overline{\mathcal{F}t} = 3072.1 \pm 0.7$$

To identify where an improvement can be achieved — review theory ingredients

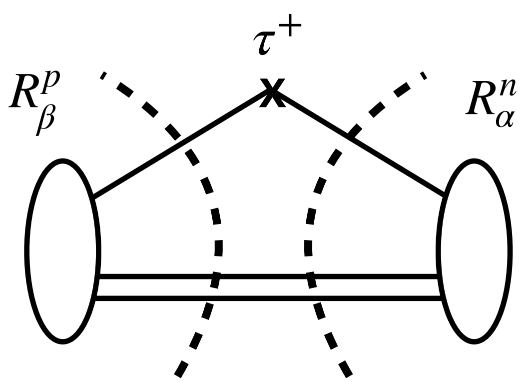
Isospin symmetry breaking in superallowed β-decay

J. Hardy, I. Towner, Phys.Rev. C 91 (2014), 025501

Fermi matrix element: $$M_F = \sum_{\alpha,\beta} \langle f | a_\alpha^\dagger a_\beta | i \rangle \langle \alpha | \tau_+ | \beta \rangle$$

$a_\alpha^\dagger$ creates a neutron in the state α
a_β annihilates a proton in the state β

Single-particle m. e. $$\langle \alpha | \tau_+ | \beta \rangle = \delta_{\alpha,\beta} \int_0^\infty R_\alpha^n(r) R_\beta^p(r) r^2 dr \equiv \delta_{\alpha,\beta} r_\alpha$$



R_α^n, R_β^p - radial WF

Without ISB: $M_F = M_0, \quad R_\alpha^n = R_\beta^p, \quad r_\alpha = 1$

With ISB: $|M_F|^2 = |M_0|^2(1 - \delta_C)$

TABLE X. Corrections δ'_R, δ_{NS}, and δ_C that are applied to experimental ft values to obtain $\mathcal{F}t$ values.

Parent nucleus	δ'_R (%)	δ_{NS} (%)	δ_{C1} (%)	δ_{C2} (%)	δ_C (%)
$T_z = -1$					
^{10}C	1.679	−0.345(35)	0.010(10)	0.165(15)	0.175(18)
^{14}O	1.543	−0.245(50)	0.055(20)	0.275(15)	0.330(25)
^{18}Ne	1.506	−0.290(35)	0.155(30)	0.405(25)	0.560(39)
^{22}Mg	1.466	−0.225(20)	0.010(10)	0.370(20)	0.380(22)
^{26}Si	1.439	−0.215(20)	0.030(10)	0.405(25)	0.435(27)
^{30}S	1.423	−0.185(15)	0.155(20)	0.700(20)	0.855(28)
^{34}Ar	1.412	−0.180(15)	0.030(10)	0.665(55)	0.695(56)
^{38}Ca	1.414	−0.175(15)	0.020(10)	0.745(70)	0.765(71)
^{42}Ti	1.427	−0.235(20)	0.105(20)	0.835(75)	0.940(78)
$T_z = 0$					
^{26m}Al	1.478	0.005(20)	0.030(10)	0.280(15)	0.310(18)
^{34}Cl	1.443	−0.085(15)	0.100(10)	0.550(45)	0.650(46)
^{38m}K	1.440	−0.100(15)	0.105(20)	0.565(50)	0.670(54)
^{42}Sc	1.453	0.035(20)	0.020(10)	0.645(55)	0.665(56)
^{46}V	1.445	−0.035(10)	0.075(30)	0.545(55)	0.620(63)
^{50}Mn	1.444	−0.040(10)	0.035(20)	0.610(50)	0.645(54)
^{54}Co	1.443	−0.035(10)	0.050(30)	0.720(60)	0.770(67)
^{62}Ga	1.459	−0.045(20)	0.275(55)	1.20(20)	1.48(21)
^{66}As	1.468	−0.060(20)	0.195(45)	1.35(40)	1.55(40)
^{70}Br	1.486	−0.085(25)	0.445(40)	1.25(25)	1.70(25)
^{74}Rb	1.499	−0.075(30)	0.115(60)	1.50(26)	1.62(27)

HT: shell model with phenomenological Woods-Saxon potential locally adjusted to:
- Masses of the isobaric multiplet T=1, 0^+
- Neutron and proton separation energies
- Known proton radii of stable isotopes

ISB in superallowed β-decay: nuclear model comparison

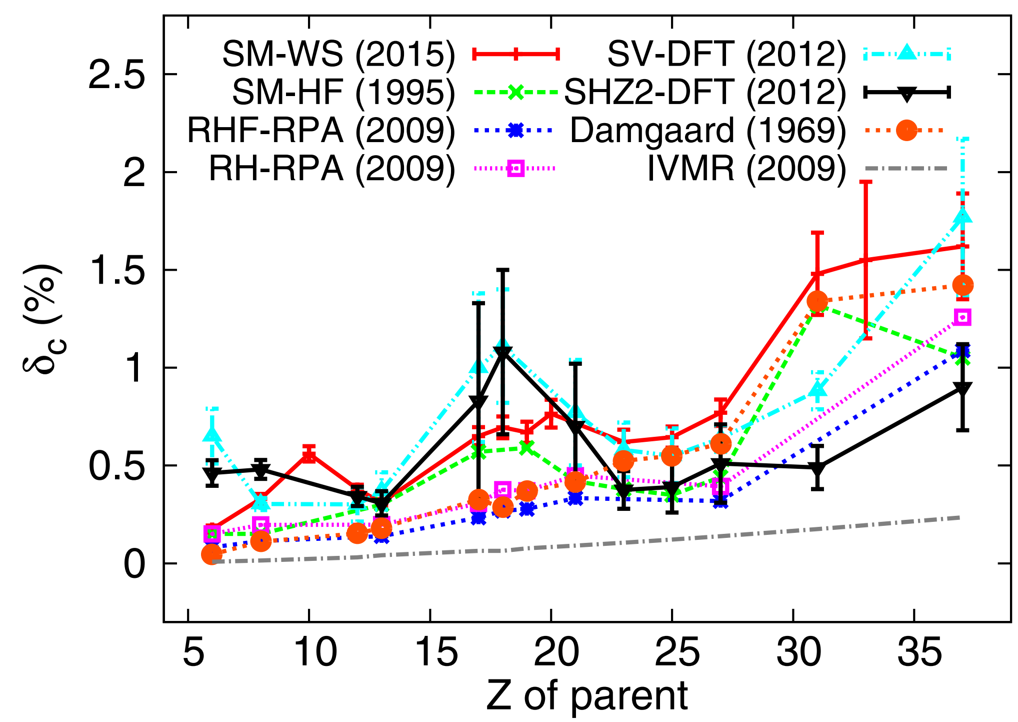
J. Hardy, I. Towner, Phys.Rev. C 91 (2014), 025501

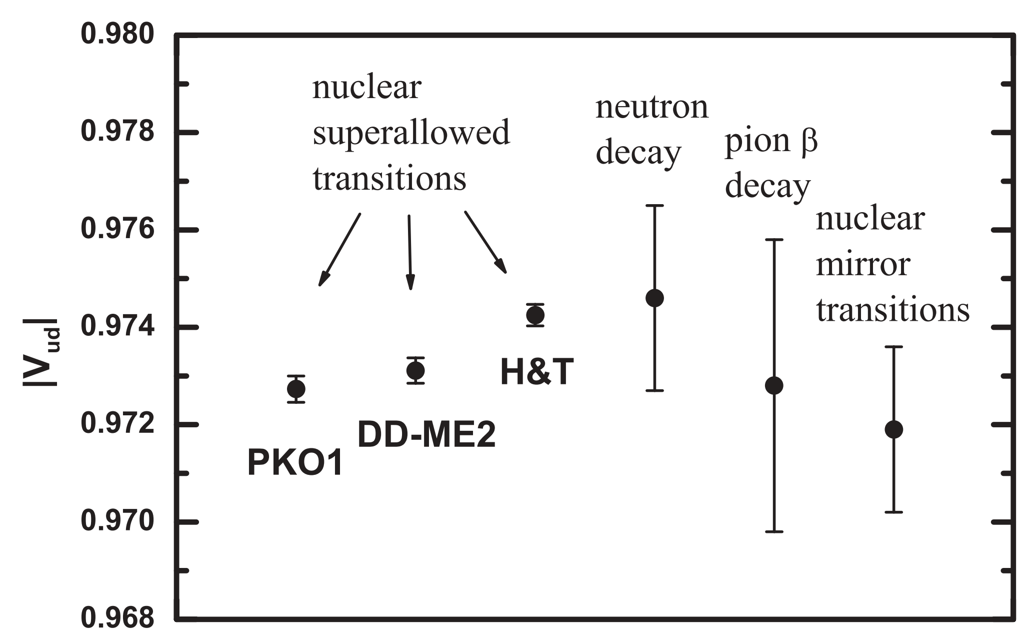
TABLE XI. Recent δ_C calculations (in percent units) based on models labeled SM-WS (shell-model, Woods-Saxon), SM-HF (shell-model, Hartree-Fock), RPA (random phase approximation), IVMR (isovector monopole resonance), and DFT (density functional theory). Also given is the χ^2/ν, χ^2 per degree of freedom, from the confidence test discussed in the text.

			RPA				
	SM-WS	SM-HF	PKO1	DD-ME2	PC-F1	IVMR[a]	DFT
$T_z = -1$							
^{10}C	0.175	0.225	0.082	0.150	0.109	0.147	0.650
^{14}O	0.330	0.310	0.114	0.197	0.150		0.303
^{22}Mg	0.380	0.260					0.301
^{34}Ar	0.695	0.540	0.268	0.376	0.379		
^{38}Ca	0.765	0.620	0.313	0.441	0.347		
$T_z = 0$							
^{26m}Al	0.310	0.440	0.139	0.198	0.159		0.370
^{34}Cl	0.650	0.695	0.234	0.307	0.316		
^{38m}K	0.670	0.745	0.278	0.371	0.294	0.434	
^{42}Sc	0.665	0.640	0.333	0.448	0.345		0.770
^{46}V	0.620	0.600					0.580
^{50}Mn	0.645	0.610					0.550
^{54}Co	0.770	0.685	0.319	0.393	0.339		0.638
^{62}Ga	1.475	1.205					0.882
^{74}Rb	1.615	1.405	1.088	1.258	0.668		1.770
χ^2/ν	1.4	6.4	4.9	3.7	6.1		4.3[b]

PKO1, DD-ME2: *H. Liang et al., Phys. Rev. C **79**, 064316 (2009)*
PC-F1: *Z. X. Li et al., Sci. China Phys. Mech. Astron. **54**, 1131 (2011)*
IVMR*: N. Auerbach, Phys. Rev. C **79**, 035502 (2009)*
DFT*: W. Satula et al.,Phys. Rev. C **86**, 054316 (2012)*

L. Xayavong, N.A. Smirnova, Phys.Rev. C 97 (2018), 024324

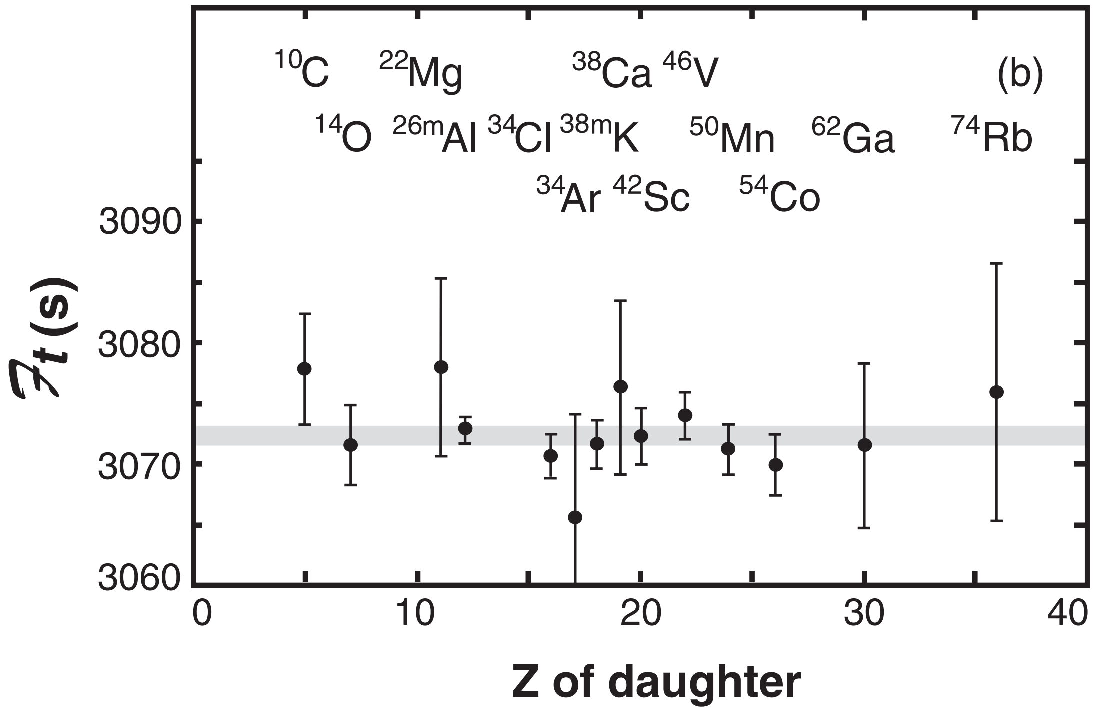




HT: χ^2 as criterium to prefer SM-WS; V_{ud} and limits on BSM strongly depend on nuclear model

ISB in superallowed β-decay and test of CVC

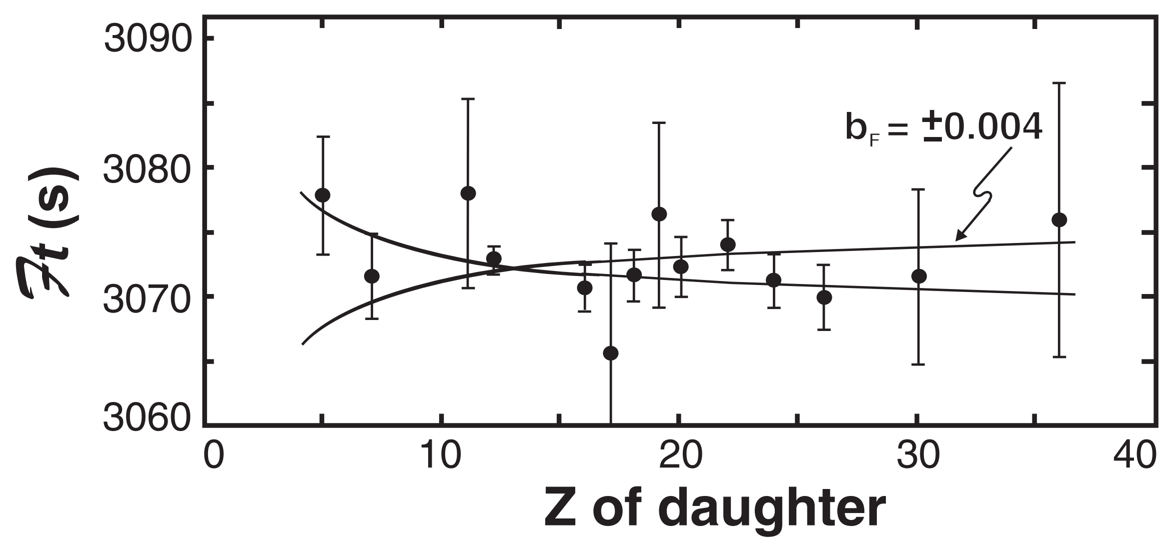
Conserved vector current hypothesis —> Ft constant



If Ft were not constant:

Presence of scalar currents - BSM

Fierz interference term $\sim b_F m_e / E_e$



Fit to 14 transitions:

Ft constant within 2×10^{-4} and $b_F = -0.0028(26)$

However: to achieve this precision the model was adjusted locally in each iso-multiplet

- Is this formalism the right tool to assess consistency amongst all the measurements?
- Shell model operates in a limited model space
- HT method criticized for using incorrect isospin formalism (G. Miller, A. Schwenk)
- Ab initio methods do not warrant such high precision

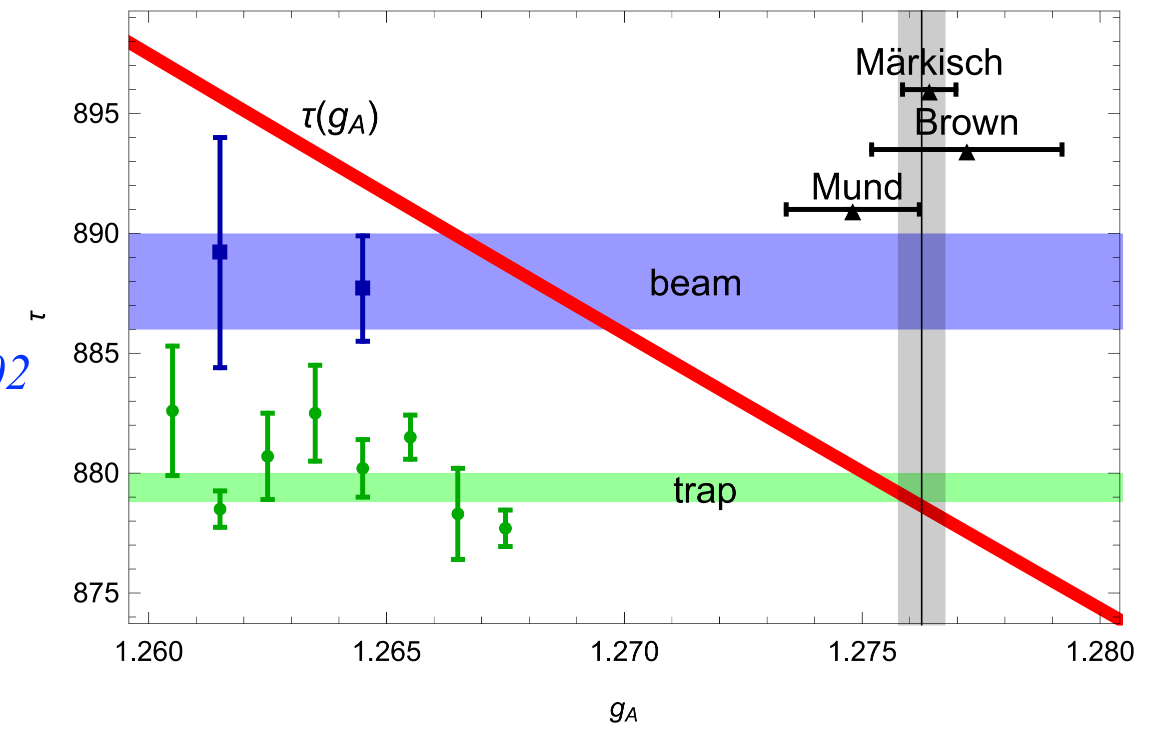
Limits on BSM crucially depend on nuclear structure corrections!

Neutron Lifetime Puzzle and Nuclear Corrections

If combining 0+-0+ nuclear and neutron decay:
Neutron lifetime and g_A tightly constrained

$$\tau_n(1 + 3g_A^2) = 5172.0(1.1)\, s$$

A. Czarnecki, B. Marciano, A. Sirlin, Phys.Rev.Lett. 120 (2018) 20, 202002



"Trap" and "beam" τ_n discrepancy:

$$\tau_n^{beam} = 888.0(2.0)\, s \qquad \tau_n^{trap} = 879.4(6)\, s$$

Plans to improve τ_n^{trap} precision to 0.1 s (including TRIGA @ Mainz)

Plans to remeasure τ_n^{beam} (BL3, J-PARC) to 0.1 s

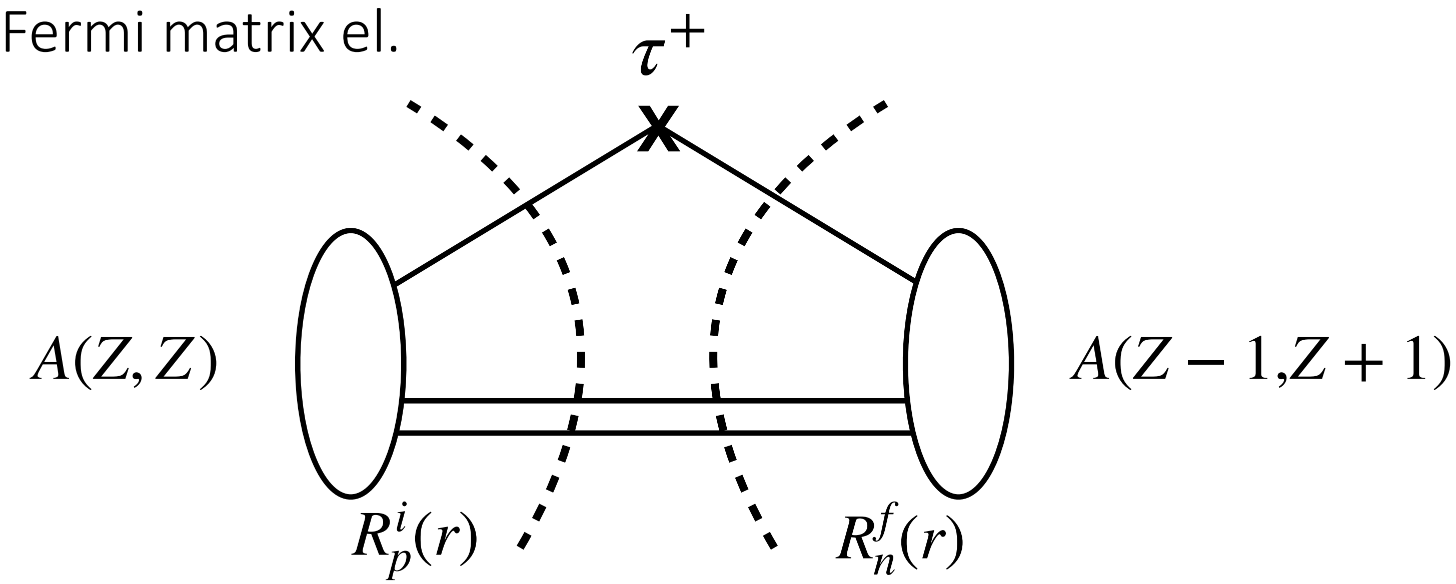
Assumption underlying the tight $g_A \leftrightarrow \tau_n$ correlation: nuclear corrections are correct

Nuclear corrections crucial for extraction of V_{ud} from free and bound neutron decay

Neutron skins as a signature of ISB effects

ISB in β-decay vs. neutron skins

ISB in Fermi matrix el.



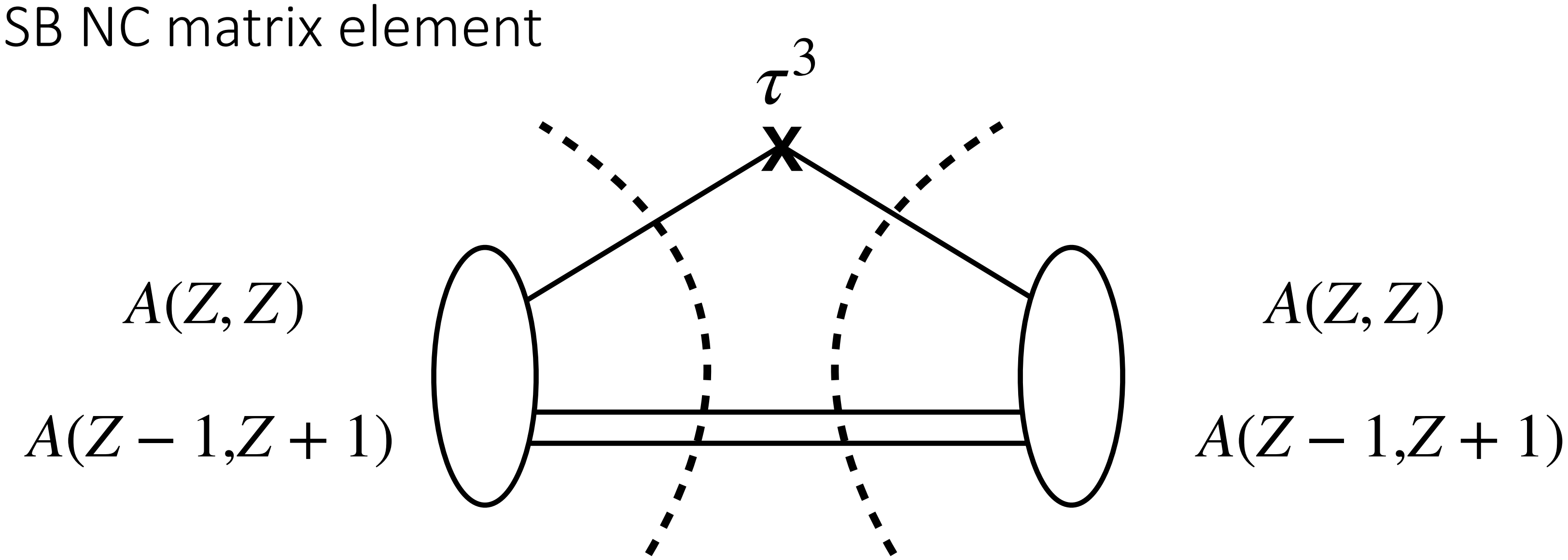
Radial functions:

$$\int d^3\vec{r}\,|R_p^i|^2 = \int d^3\vec{r}\,|R_n^f|^2 = 1$$

Radial overlap and ISB correction

$$\int d^3\vec{r} R_p^i R_n^f = 1 - \frac{\delta_C}{2}$$

ISB NC matrix element



$$\int d^3\vec{r}(|R_p|^2 - |R_n|^2) = 0$$

But neutron skin is nonzero

$$\int d^3\vec{r} r^2(|R_p|^2 - |R_n|^2) = \langle r_n^2 \rangle - \langle r_p^2 \rangle$$

ISB in $|i\rangle \propto \; R_n^i(r) - R_p^i(r)$ ISB in $|f\rangle \propto \; R_n^f(r) - R_p^f(r)$

Analog of Ademollo-Gatto theorem: δ_C is quadratic in ISB

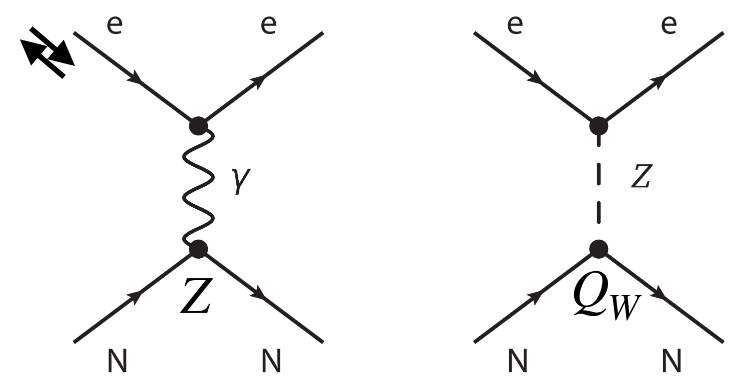
G.A. Miller, A. Schwenk, Phys.Rev.C 78 (2008) 035501; Phys.Rev.C 80 (2009) 064319

Neutron skin is linear in ISB

Weak Charges and Radii from PVES

Elastic scattering of longitudinally polarized e- beam
Parity-violating asymmetry

$$A^{\rm PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\frac{Q_W}{Z}(1+\Delta)$$



Weak charge —> weak mixing angle $Q_W(Z,N) = -N + Z(1-4\sin^2\theta_W)$

Tuesday: Ayres, Paul

Correction term Δ for spin-0 nuclei: neutron skin $\Delta \approx -(R_{wk}^2 - R_{ch}^2)Q^2/6 \approx -(R_n^2 - R_p^2)Q^2/6$

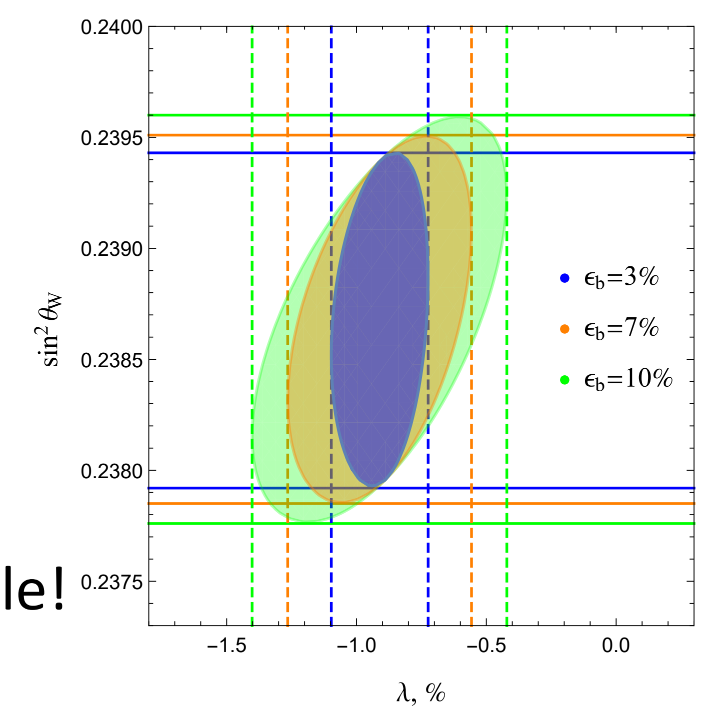
Wednesday: Jorge, Juliette; Thursday: Concettina

Feasibility study for C-12 @ MESA: forward + backward measurement

O. Koshchii, J. Erler, MG, C.J. Horowitz, J. Piekarewicz, X. Roca-Maza, C.-Y. Seng, H. Spiesberger, arXiv:2005.00479

Forward / Backward precision ϵ^f / ϵ^b

(ϵ^f, ϵ^b)	$\left(\frac{\delta\sin^2\theta_W}{\sin^2\theta_W}, \frac{\delta R_W}{R_W}\right)$
$(0.3\,\%, 10\%)$	$(0.39\,\%, 0.5\%)$
$(0.3\,\%, 7\%)$	$(0.35\,\%, 0.4\%)$
$(0.3\,\%, 3\%)$	$(0.32\,\%, 0.2\%)$



Simultaneous extraction of weak charge and radius at few per mille feasible!

Sasha's talk on Wednesday

Neutron skins of symmetric nuclei as ISB signature

Usually studied in neutron-rich nuclei —> symmetry energy $S(\rho)$ —> nuclear EOS

$$\frac{E}{A}(\rho,\beta) = \frac{E}{A}(\rho,\beta=0) + S(\rho)\beta^2.$$

E/A — energy per particle
ρ — local density
$\beta = (\rho_n - \rho_p)/\rho$ - neutron/proton asymmetry

C-12 symmetric, N=Z —> skin due to isospin symmetry breaking

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Nuclear Symmetry Energy and the Breaking of the Isospin Symmetry: How Do They Reconcile with Each Other?

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We analyze and propose a solution to the apparent inconsistency between our current knowledge of the equation of state of asymmetric nuclear matter, the energy of the isobaric analog state (IAS) in a heavy nucleus such as ^{208}Pb, and the isospin symmetry breaking forces in the nuclear medium. This is achieved by performing state-of-the-art Hartree-Fock plus random phase approximation calculations of the IAS that include all isospin symmetry breaking contributions. To this aim, we propose a new effective interaction that is successful in reproducing the IAS excitation energy without compromising other properties of finite nuclei.

DOI: 10.1103/PhysRevLett.120.202501

Talk by Jorge on Wednesday

New context for PVES: ISB corrections to superallowed nuclear β decays

Precise weak radii of stable 0^+ daughter nuclei @ MESA

Unique task for MESA: weak skins of stable daughter nuclei in 5 best-measured decays:

$$^{26m}Al \rightarrow \mathbf{^{26}Mg},\ ^{34}Cl \rightarrow \mathbf{^{34}S},\ ^{38m}K \rightarrow \mathbf{^{38}Ar},\ ^{42}Sc \rightarrow \mathbf{^{42}Ca},\ ^{46}V \rightarrow \mathbf{^{46}Ti}$$

Available information on the 5 stable 0+ daughter nuclides: live chart of nuclides

https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Isotope (Z,N)	Abundance	Charge radius (fm)	S_n (MeV)	S_p (MeV)	E_x in MeV (J^π)
^{26}Mg(12,14)	11.01%	3.0337(18)	11.093	14.145	1.808(2+), 2.938(2+), 3.588(0+)
^{34}S(16,18)	4.25%	3.2847(21)	11.417	10.883	2.127(2+), 3.304(2+), 3.916(0+)
^{38}Ar(18,20)	0.0629%	3.4028(19)	11.838	10.242	2.167(2+), 3.377(0+), 3.810(3-)
^{42}Ca(20,22)	0.647%	3.5081(21)	11.480	10.2776	1.524(2+), 1.837(0+), 2.424 (2+)
^{46}Ti(22,24)	8.25%	3.6070(22)	13.189	10.344	0.889(2+), 2.009(4+), 2.611(0+)

$\frac{\delta R_{ch}}{R_{ch}} \approx 0.06\,\%$

Skin for N = Z+2 small: small neutron excess vs. Coulomb repulsion of protons

Direct access to ISB via $R^2_{wk} - R^2_{ch} \approx R^2_n - R^2_p$ —> theory to relate to δ_C Work in progress with Sonia Bacca

Additionally: charge radii of unstable 0^+ isotopes at rare isotope facilities (FRIB, GSI, TRIUMF)

SnowMass2021 https://snowmass21.org/start: Call for EOI

Plan submitting an EOI (with Albert Young — part of FRIB)

Summary

- Nuclear structure plays a crucial role in low-energy precision tests
- Nuclear beta decays: ISB effects in nuclei - major ingredient on the path to V_{ud} and CKM unitarity
- Neutron skins of selected daughter nuclei as an independent constraint on δ_C
- A richer context for PVES — enhanced physics output

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Upcoming MITP *presence* workshop

“Physics Opportunities with the Gamma Factory”, November 30 - December 4, 2020
Organizers: Dmitry Budker, Witek Krasny, MG, Adriana Palffy, Andrei Surzhikov

A teaser at this workshop:
Talk by W. Krasny on “Tertiary $\nu(\bar{\nu})$ beams at Gamma Factory” - Thursday, July 30

Thank you for your attention

and

Looking forward to an exciting workshop!