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Investigating fundamental symmetries at ARIEL

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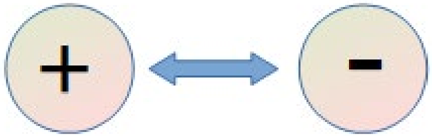
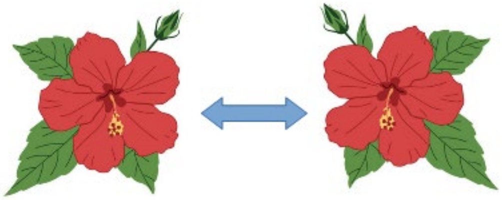
No rigorous definition of “fundamental symmetries”!

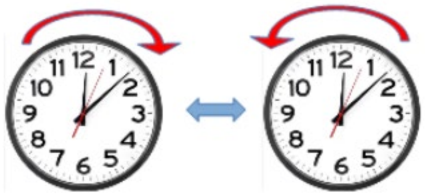
Obvious examples are discrete symmetries:



Charge conjugation (C)



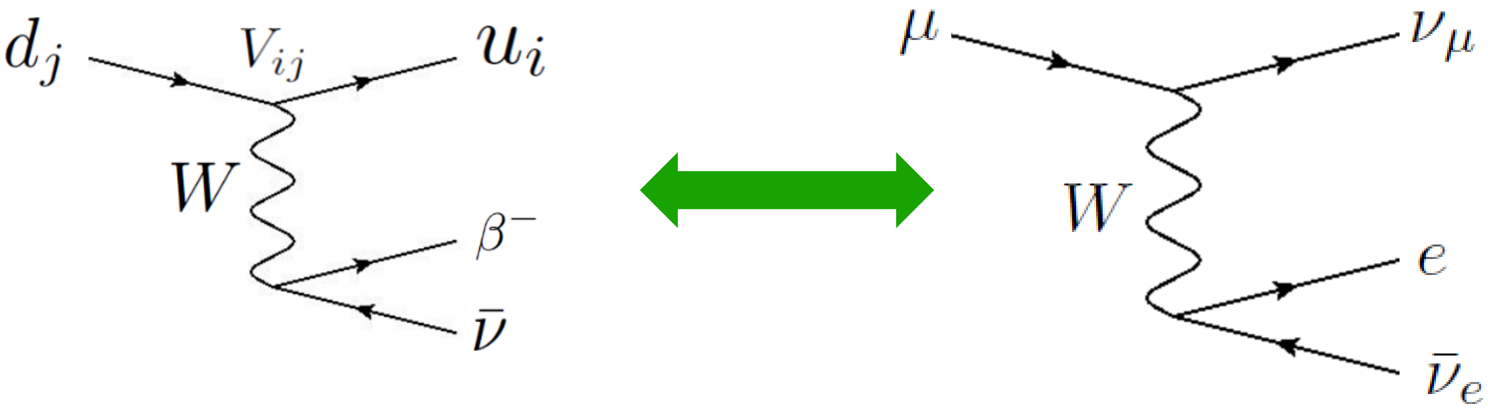
Parity (P)



Time reversal (T), etc

But there are also symmetries due to SM gauge structures

Example: **Universality** in charged weak interaction:

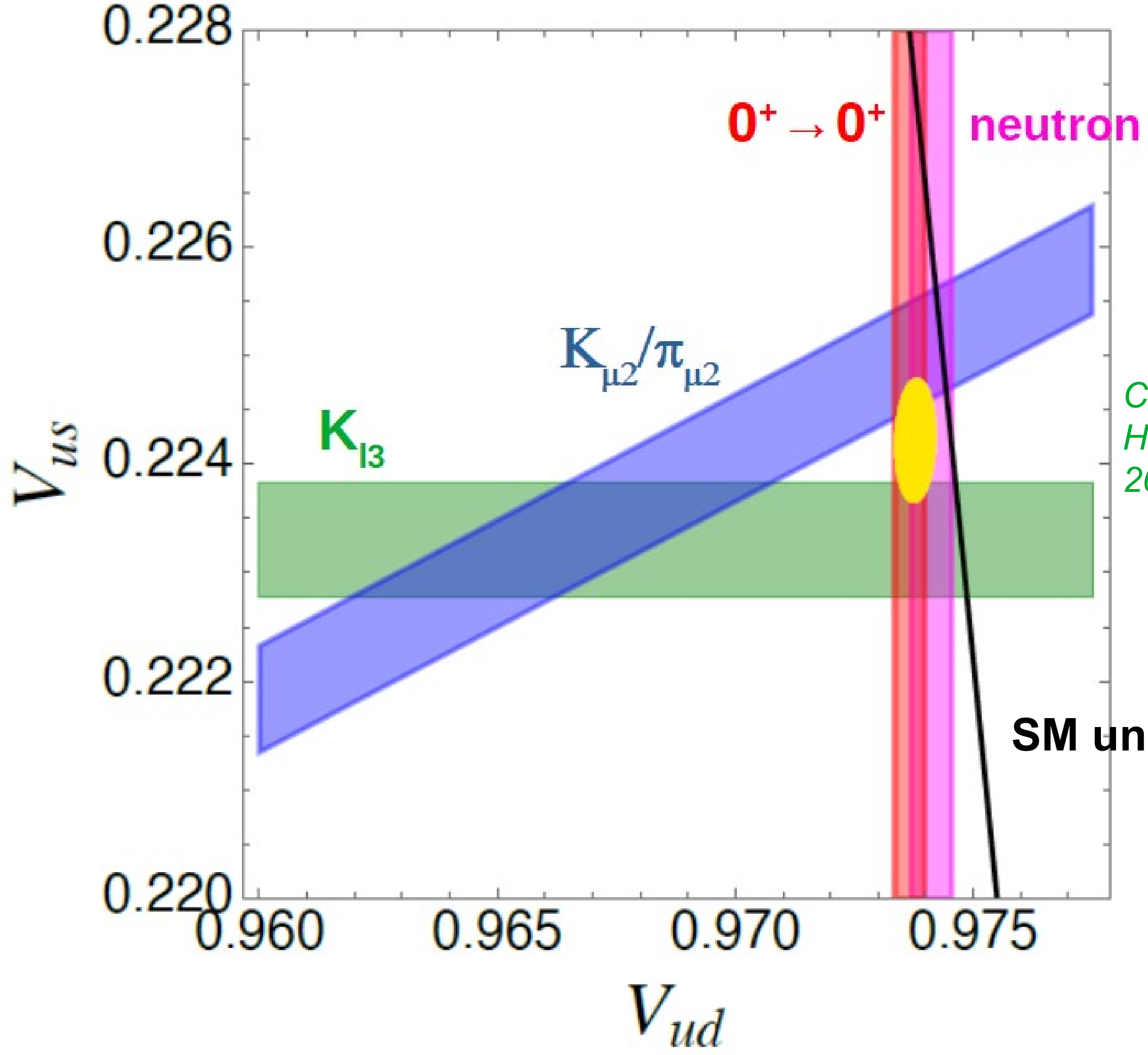


Universality ==> Unitarity of the CKM matrix

Can be tested at **0.01%** level! Probes new physics at the scale:

$$\left(\frac{v_{\mathrm{H}}}{\Lambda_{\mathrm{BSM}}}\right)^2 \sim 0.01\% \quad \Longrightarrow \quad \Lambda_{\mathrm{BSM}} \sim 20\ \mathrm{TeV}$$

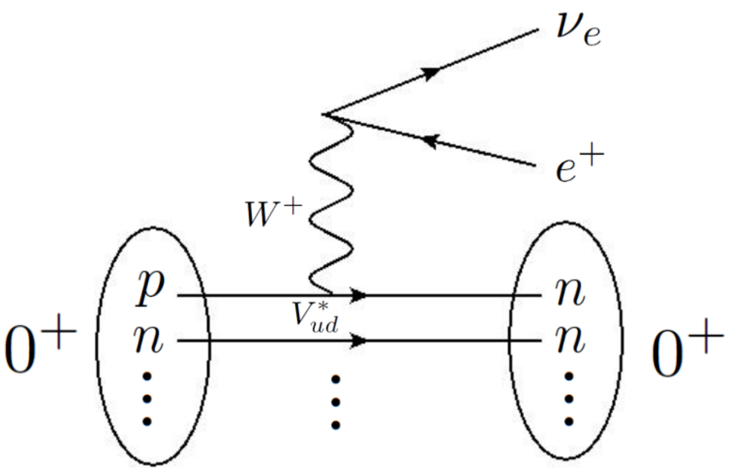
“Cabibbo angle anomaly”: Unitarity deficit ~3σ



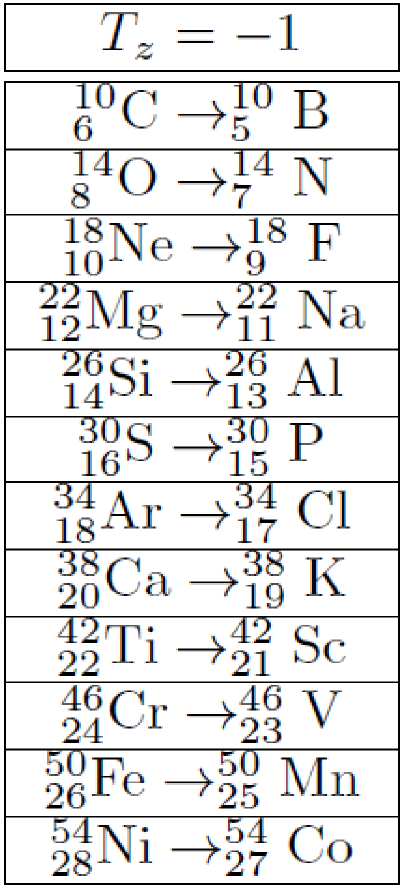
Cirigliano, Crivellin, Hoferichter and Moulson, 2023 PLB

New physics?

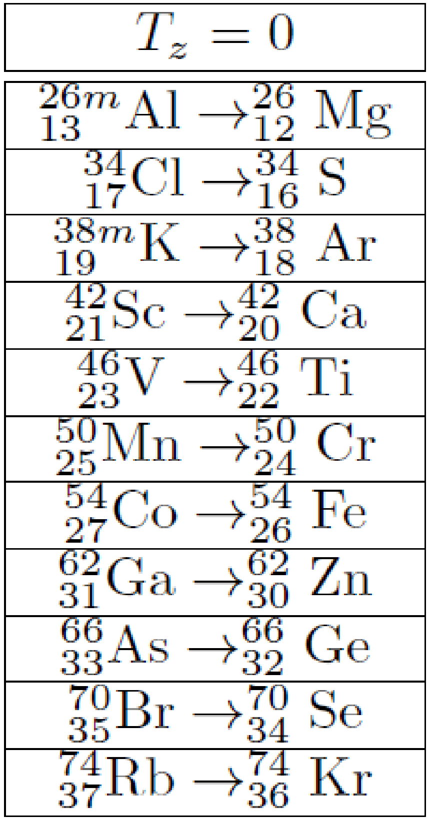
“Superallowed” beta decays of **T=1, J^p=0$^+$ nuclei**



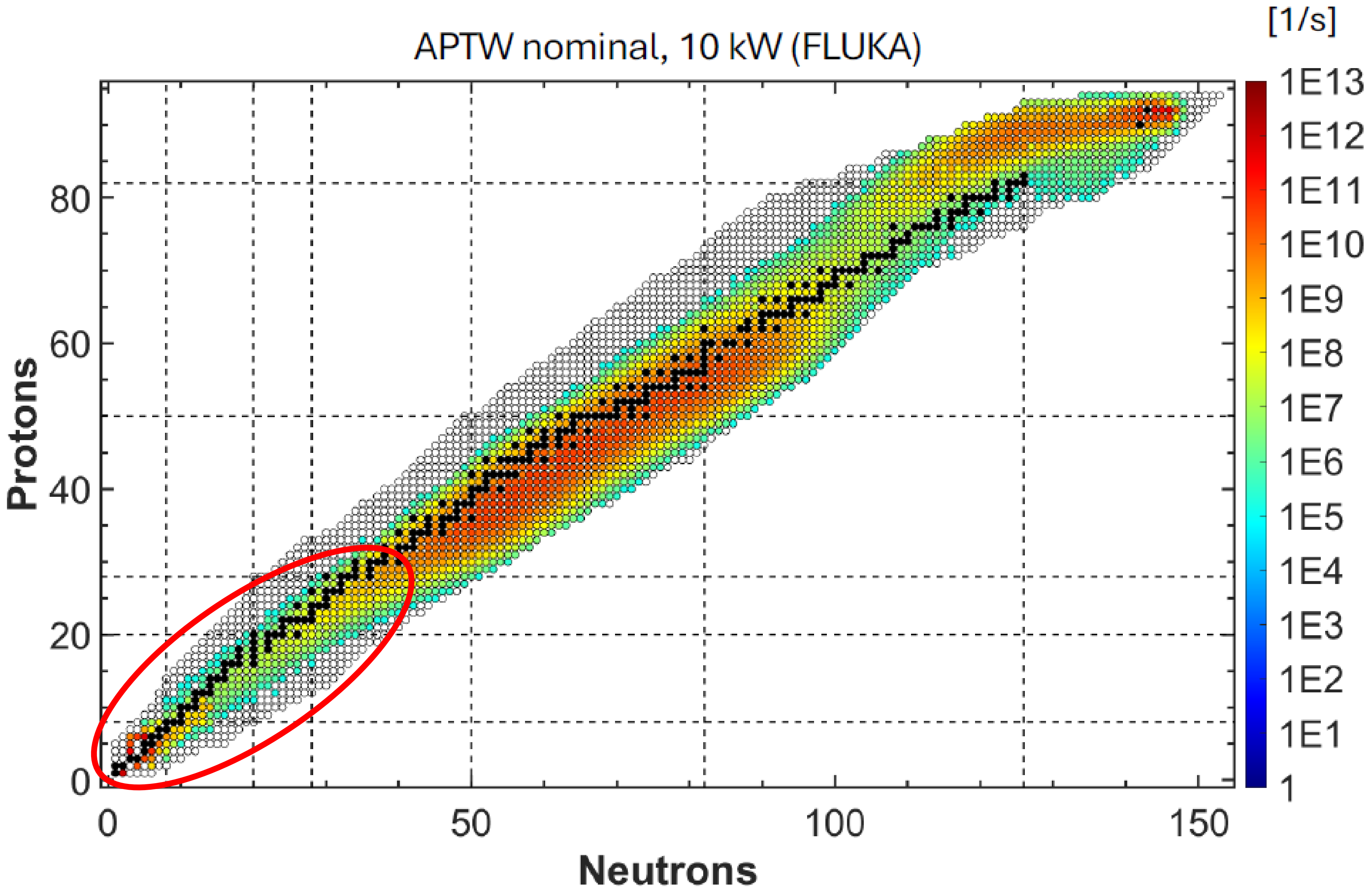
Provide best determination of **V$_{ud}$**



$T_z = -1$
${}^{10}_{6}\mathrm{C} \to {}^{10}_{5}\mathrm{B}$
${}^{14}_{8}\mathrm{O} \to {}^{14}_{7}\mathrm{N}$
${}^{18}_{10}\mathrm{Ne} \to {}^{18}_{9}\mathrm{F}$
${}^{22}_{12}\mathrm{Mg} \to {}^{22}_{11}\mathrm{Na}$
${}^{26}_{14}\mathrm{Si} \to {}^{26}_{13}\mathrm{Al}$
${}^{30}_{16}\mathrm{S} \to {}^{30}_{15}\mathrm{P}$
${}^{34}_{18}\mathrm{Ar} \to {}^{34}_{17}\mathrm{Cl}$
${}^{38}_{20}\mathrm{Ca} \to {}^{38}_{19}\mathrm{K}$
${}^{42}_{22}\mathrm{Ti} \to {}^{42}_{21}\mathrm{Sc}$
${}^{46}_{24}\mathrm{Cr} \to {}^{46}_{23}\mathrm{V}$
${}^{50}_{26}\mathrm{Fe} \to {}^{50}_{25}\mathrm{Mn}$
${}^{54}_{28}\mathrm{Ni} \to {}^{54}_{27}\mathrm{Co}$



$T_z = 0$
${}^{26m}_{13}\mathrm{Al} \to {}^{26}_{12}\mathrm{Mg}$
${}^{34}_{17}\mathrm{Cl} \to {}^{34}_{16}\mathrm{S}$
${}^{38m}_{19}\mathrm{K} \to {}^{38}_{18}\mathrm{Ar}$
${}^{42}_{21}\mathrm{Sc} \to {}^{42}_{20}\mathrm{Ca}$
${}^{46}_{23}\mathrm{V} \to {}^{46}_{22}\mathrm{Ti}$
${}^{50}_{25}\mathrm{Mn} \to {}^{50}_{24}\mathrm{Cr}$
${}^{54}_{27}\mathrm{Co} \to {}^{54}_{26}\mathrm{Fe}$
${}^{62}_{31}\mathrm{Ga} \to {}^{62}_{30}\mathrm{Zn}$
${}^{66}_{33}\mathrm{As} \to {}^{66}_{32}\mathrm{Ge}$
${}^{70}_{35}\mathrm{Br} \to {}^{70}_{34}\mathrm{Se}$
${}^{74}_{37}\mathrm{Rb} \to {}^{74}_{36}\mathrm{Kr}$



Superallowed decay candidates accessible at
Ariel Proton Target West (APTW)

Extraction of V_{ud} from superallowed beta decays

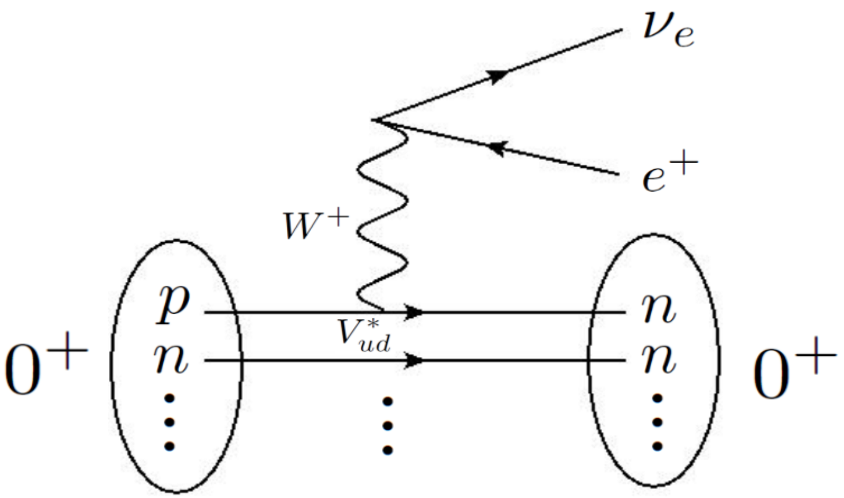
$$|V_{ud}|^2 = \frac{2984.431(3)\,\mathrm{s}}{\underbrace{\mathcal{F}t}(1+\Delta_R^V)}$$

Direct **experimental inputs**:

1. Total lifetime
2. Branching ratio
3. Q_{EC} value

But there are also **THEORY INPUTS** that would benefit from experiments!

Fermi decay matrix element



$$|M_F|^2 = |\langle f|\hat{\tau}_+|i\rangle|^2 \approx 2$$

Thanks to another approximate symmetry: **Isospin**

At 0.01% precision, **isospin symmetry breaking (ISB)** corrections must be included!

$$|M_F|^2 = |\langle f|\hat{\tau}_+|i\rangle|^2 = |M_F^0|^2(1-\delta_C)$$

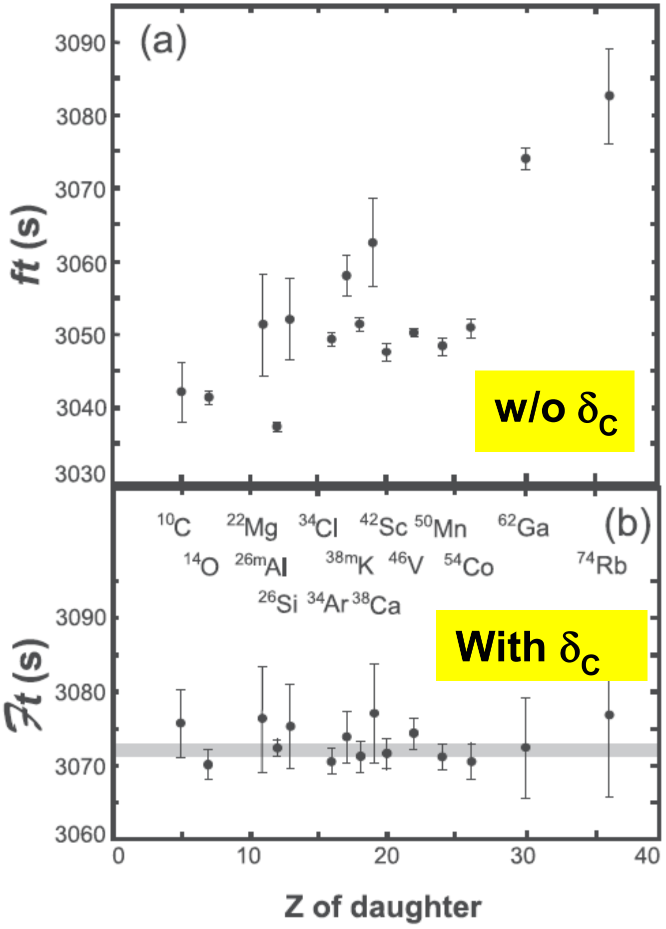
$$H = H_0 + \boxed{V}$$

ISB potential due to EM effects

$$\delta_C = \mathcal{O}(V^2)$$

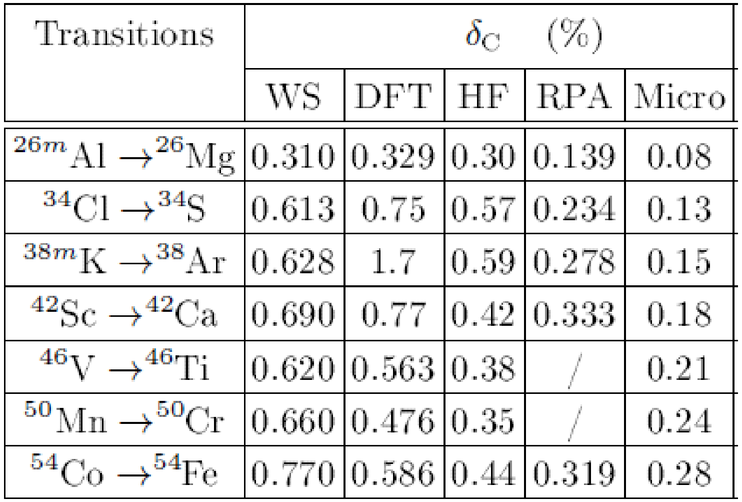
0.1%~1%

Crucial to test **conserved vector current (CVC)** assumption



Hardy and Towner, 2020 PRC

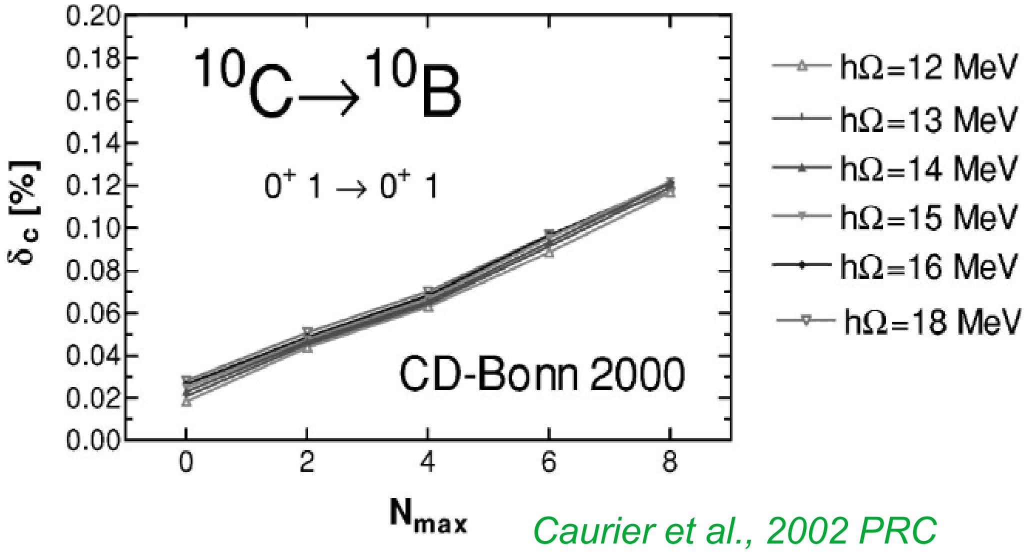
- **Computing δ_c**: Classic problem over ***6 decades***!



Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}$	0.310	0.329	0.30	0.139	0.08
$^{34}\mathrm{Cl} \rightarrow {}^{34}\mathrm{S}$	0.613	0.75	0.57	0.234	0.13
$^{38m}\mathrm{K} \rightarrow {}^{38}\mathrm{Ar}$	0.628	1.7	0.59	0.278	0.15
$^{42}\mathrm{Sc} \rightarrow {}^{42}\mathrm{Ca}$	0.690	0.77	0.42	0.333	0.18
$^{46}\mathrm{V} \rightarrow {}^{46}\mathrm{Ti}$	0.620	0.563	0.38	/	0.21
$^{50}\mathrm{Mn} \rightarrow {}^{50}\mathrm{Cr}$	0.660	0.476	0.35	/	0.24
$^{54}\mathrm{Co} \rightarrow {}^{54}\mathrm{Fe}$	0.770	0.586	0.44	0.319	0.28

(Selected results)

Model calculations showed large variations



Caurier et al., 2002 PRC

Ab initio calculations suffer from non-convergence

…and spurious ISB effect

Farren and Stroberg, 2412.10693

Inferring δ_C from experiment?

Nuclear mass splitting: $\delta E_n = {}_0\langle n|V|n\rangle_0$ **X**

$$|n\rangle = |n\rangle_0 + \underbrace{\sum_{k\neq n} |k\rangle_0 \frac{{}_0\langle k|V|n\rangle_0}{E_n^{(0)} - E_k^{(0)}}}_{\text{We need this}} + \ldots$$

ISB can be probed through the **variation of charge radii within the same nuclear isomultiplet**

Consider T=1 system. The non-zeroness of

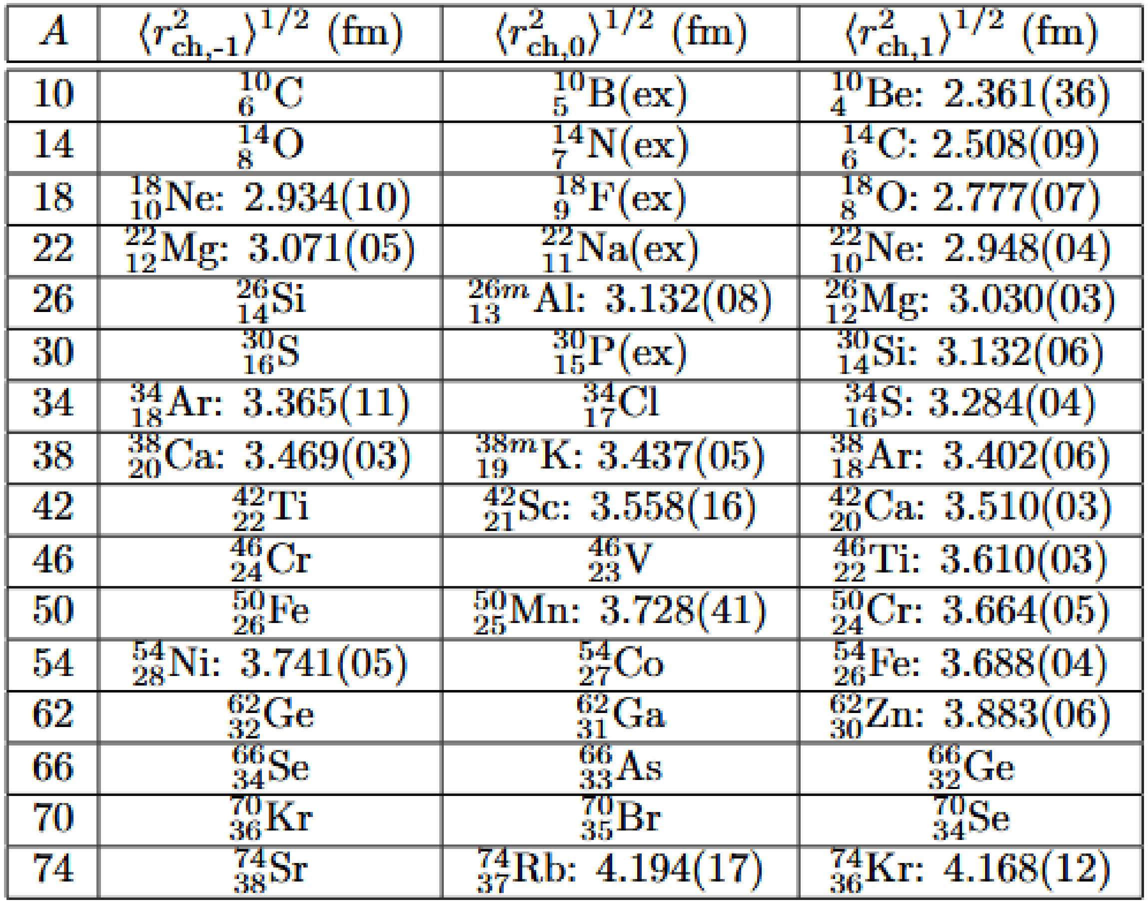
$$\boxed{\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_{+1} r^2_{\mathrm{ch},+1} + Z_{-1} r^2_{\mathrm{ch,\text{-}1}}\right) - Z_0 r^2_{\mathrm{ch},0}}$$

signifies ISB.

Seng and Gorchtein, 2023 PLB; 2024 PRC

Could serve as **important benchmark for δ_C calculation**

List of T=1 nuclei and charge radii data



A	$\langle r^2_{\mathrm{ch},-1}\rangle^{1/2}$ (fm)	$\langle r^2_{\mathrm{ch},0}\rangle^{1/2}$ (fm)	$\langle r^2_{\mathrm{ch},1}\rangle^{1/2}$ (fm)
10	$^{10}_{6}$C	$^{10}_{5}$B(ex)	$^{10}_{4}$Be: 2.361(36)
14	$^{14}_{8}$O	$^{14}_{7}$N(ex)	$^{14}_{6}$C: 2.508(09)
18	$^{18}_{10}$Ne: 2.934(10)	$^{18}_{9}$F(ex)	$^{18}_{8}$O: 2.777(07)
22	$^{22}_{12}$Mg: 3.071(05)	$^{22}_{11}$Na(ex)	$^{22}_{10}$Ne: 2.948(04)
26	$^{26}_{14}$Si	$^{26m}_{13}$Al: 3.132(08)	$^{26}_{12}$Mg: 3.030(03)
30	$^{30}_{16}$S	$^{30}_{15}$P(ex)	$^{30}_{14}$Si: 3.132(06)
34	$^{34}_{18}$Ar: 3.365(11)	$^{34}_{17}$Cl	$^{34}_{16}$S: 3.284(04)
38	$^{38}_{20}$Ca: 3.469(03)	$^{38m}_{19}$K: 3.437(05)	$^{38}_{18}$Ar: 3.402(06)
42	$^{42}_{22}$Ti	$^{42}_{21}$Sc: 3.558(16)	$^{42}_{20}$Ca: 3.510(03)
46	$^{46}_{24}$Cr	$^{46}_{23}$V	$^{46}_{22}$Ti: 3.610(03)
50	$^{50}_{26}$Fe	$^{50}_{25}$Mn: 3.728(41)	$^{50}_{24}$Cr: 3.664(05)
54	$^{54}_{28}$Ni: 3.741(05)	$^{54}_{27}$Co	$^{54}_{26}$Fe: 3.688(04)
62	$^{62}_{32}$Ge	$^{62}_{31}$Ga	$^{62}_{30}$Zn: 3.883(06)
66	$^{66}_{34}$Se	$^{66}_{33}$As	$^{66}_{32}$Ge
70	$^{70}_{36}$Kr	$^{70}_{35}$Br	$^{70}_{34}$Se
74	$^{74}_{38}$Sr	$^{74}_{37}$Rb: 4.194(17)	$^{74}_{36}$Kr: 4.168(12)

B.Ohayon, 2025 Atom.Data Nucl.Data Tabl.

Only A=38 has 3 measured radii; $\Delta M_B^{(1)}$ consistent with zero.

Semi-empirical test of isospin symmetry with charge radii

B.Ohayon, 2025 Atom.Data Nucl.Data Tabl.

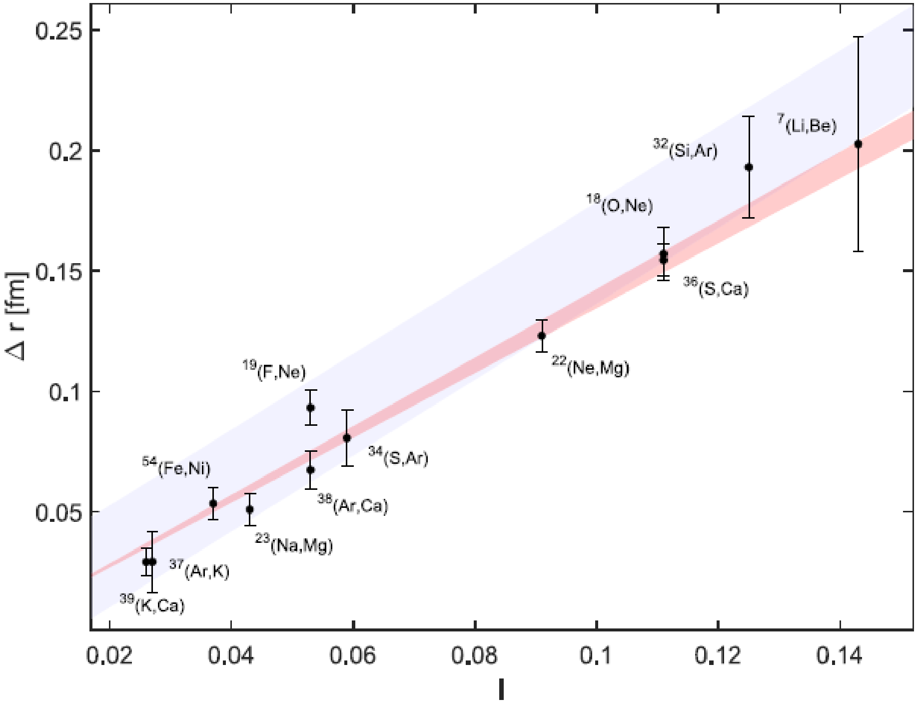
Starting from the known T_z=+1 radius:

Step 1: **Mirror shift parameterization**

$$r_{+1} \longrightarrow r_{-1}$$

$$\Delta r \equiv r_{N,Z}(I) - r_{Z,N}(I) = 1.381(34) \times I \text{ fm}$$

$$I \equiv \frac{N-Z}{A}$$

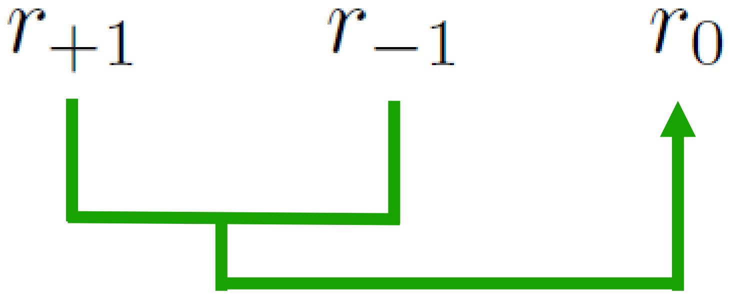


Semi-empirical test of isospin symmetry with charge radii

B.Ohayon, 2025 Atom.Data Nucl.Data Tabl.

Starting from the known T_z=+1 radius:

Step 2: **Assuming isospin symmetry**

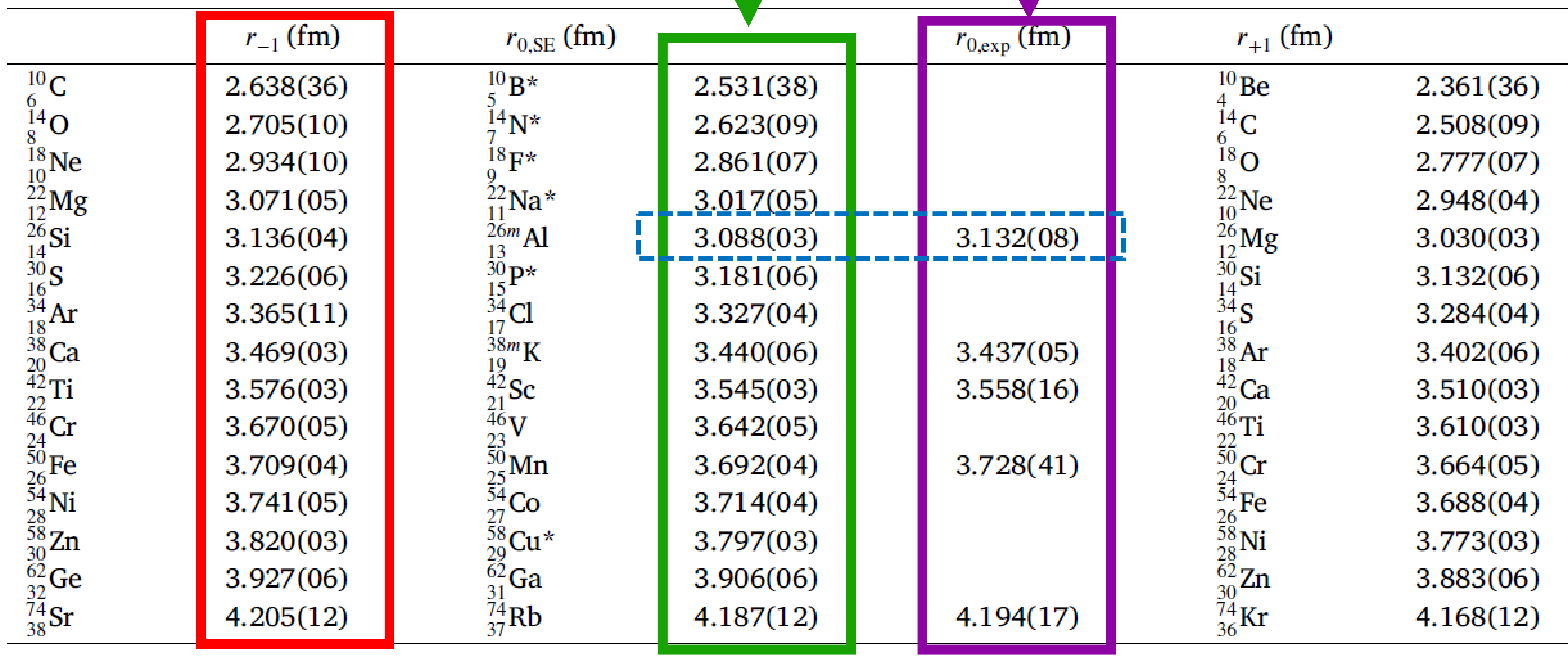


Then, compare the deduced r_0 with the measured ones (if available)

Some obtained from Step 1

Obtained from Step 2

Experiment



	r_{-1} (fm)		$r_{0,\mathrm{SE}}$ (fm)	$r_{0,\mathrm{exp}}$ (fm)		r_{+1} (fm)
${}^{10}_{6}\mathrm{C}$	2.638(36)	${}^{10}_{5}\mathrm{B}^*$	2.531(38)		${}^{10}_{4}\mathrm{Be}$	2.361(36)
${}^{14}_{8}\mathrm{O}$	2.705(10)	${}^{14}_{7}\mathrm{N}^*$	2.623(09)		${}^{14}_{6}\mathrm{C}$	2.508(09)
${}^{18}_{10}\mathrm{Ne}$	2.934(10)	${}^{18}_{9}\mathrm{F}^*$	2.861(07)		${}^{18}_{8}\mathrm{O}$	2.777(07)
${}^{22}_{12}\mathrm{Mg}$	3.071(05)	${}^{22}_{11}\mathrm{Na}^*$	3.017(05)		${}^{22}_{10}\mathrm{Ne}$	2.948(04)
${}^{26}_{14}\mathrm{Si}$	3.136(04)	${}^{26m}_{13}\mathrm{Al}$	3.088(03)	3.132(08)	${}^{26}_{12}\mathrm{Mg}$	3.030(03)
${}^{30}_{16}\mathrm{S}$	3.226(06)	${}^{30}_{15}\mathrm{P}^*$	3.181(06)		${}^{30}_{14}\mathrm{Si}$	3.132(06)
${}^{34}_{18}\mathrm{Ar}$	3.365(11)	${}^{34}_{17}\mathrm{Cl}$	3.327(04)		${}^{34}_{16}\mathrm{S}$	3.284(04)
${}^{38}_{20}\mathrm{Ca}$	3.469(03)	${}^{38m}_{19}\mathrm{K}$	3.440(06)	3.437(05)	${}^{38}_{18}\mathrm{Ar}$	3.402(06)
${}^{42}_{22}\mathrm{Ti}$	3.576(03)	${}^{42}_{21}\mathrm{Sc}$	3.545(03)	3.558(16)	${}^{42}_{20}\mathrm{Ca}$	3.510(03)
${}^{46}_{24}\mathrm{Cr}$	3.670(05)	${}^{46}_{23}\mathrm{V}$	3.642(05)		${}^{46}_{22}\mathrm{Ti}$	3.610(03)
${}^{50}_{26}\mathrm{Fe}$	3.709(04)	${}^{50}_{25}\mathrm{Mn}$	3.692(04)	3.728(41)	${}^{50}_{24}\mathrm{Cr}$	3.664(05)
${}^{54}_{28}\mathrm{Ni}$	3.741(05)	${}^{54}_{27}\mathrm{Co}$	3.714(04)		${}^{54}_{26}\mathrm{Fe}$	3.688(04)
${}^{58}_{30}\mathrm{Zn}$	3.820(03)	${}^{58}_{29}\mathrm{Cu}^*$	3.797(03)		${}^{58}_{28}\mathrm{Ni}$	3.773(03)
${}^{62}_{32}\mathrm{Ge}$	3.927(06)	${}^{62}_{31}\mathrm{Ga}$	3.906(06)		${}^{62}_{30}\mathrm{Zn}$	3.883(06)
${}^{74}_{38}\mathrm{Sr}$	4.205(12)	${}^{74}_{37}\mathrm{Rb}$	4.187(12)	4.194(17)	${}^{74}_{36}\mathrm{Kr}$	4.168(12)

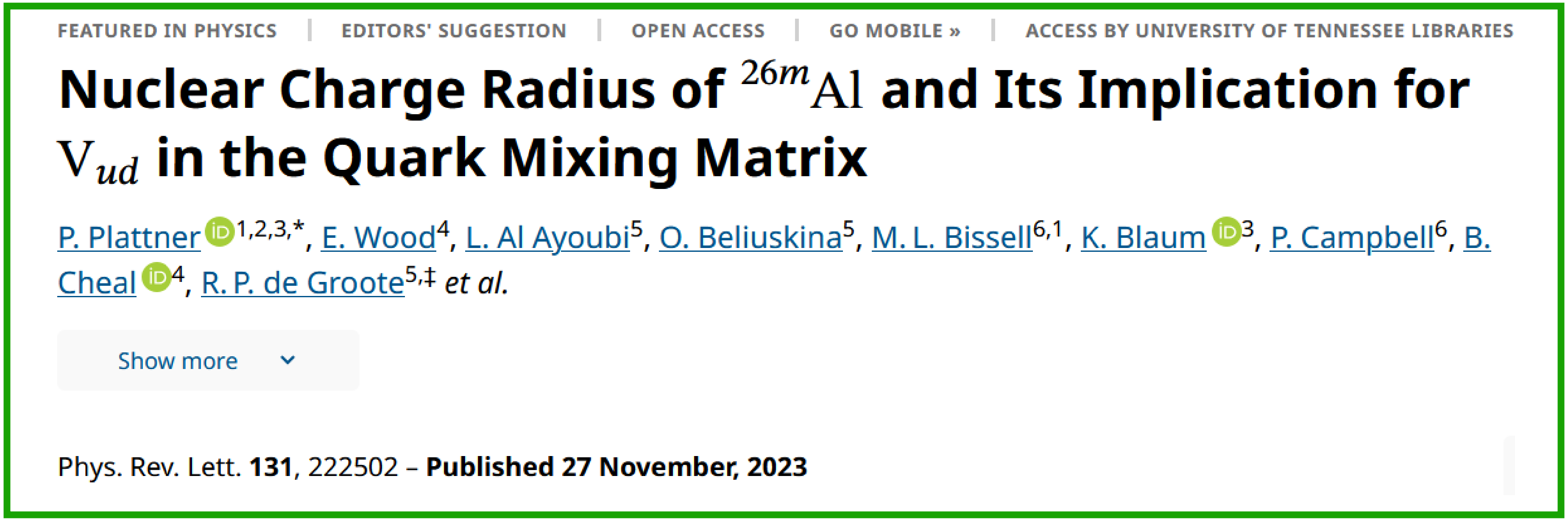
B.Ohayon, 2025 Atom.Data Nucl.Data Tabl.

Large ISB signal in the **A=26** isotriplet?

Similar observation from IMSRG calculation

Bingcheng He et al., in preparation

^{26m}Al radius only measured recently (ISOLDE+IGISOL):



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Nuclear Charge Radius of ^{26m}Al and Its Implication for V_{ud} in the Quark Mixing Matrix

P. Plattner[1,2,3,*], E. Wood[4], L. Al Ayoubi[5], O. Beliuskina[5], M. L. Bissell[6,1], K. Blaum[3], P. Campbell[6], B. Cheal[4], R. P. de Groote[5,‡] *et al.*

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Phys. Rev. Lett. **131**, 222502 – **Published 27 November, 2023**

Experimental issue? Or Large ISB signal?

ISB effect can be directly probed by measuring **^{26}Si radius**

Required measurement: **Isotope shift**, e.g. **^{28}Si → ^{26}Si**

Extracting radii from unstable nuclei

Isotope shift: Measured experimentally from laser spectroscopy

$$\delta\nu^{A,A'} \approx K \cdot \frac{M_A - M_{A'}}{M_A M_{A'}} + F \cdot \delta\langle r^2\rangle^{A,A'}$$

Mass-shift factor

Field-shift factor

Si possesses 3 stable isotopes: ^{28}Si, ^{29}Si, ^{30}Si,
so K and F can be deduced from **King-plot analysis**!

Measurement of $\delta\nu^{A,A'}$ will unambiguously determine the **^{26}Si charge radius**.

Summary

- I discussed two "fundamental symmetries": **weak interaction universality** and **isospin symmetry**, in the context of superallowed nuclear beta decays
- Relevant nuclei accessible at APTW
- Theoretical calculations of ISB effect contain large uncertainty, and can benefit from charge radii measurements
- A=26 isotriplet has potential to probe large ISB effect. Measurement of ^{26}Si charge radius is desired.

Thanks for your attention!