Effects of dispersion parity-violating interactions in atoms

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Based on

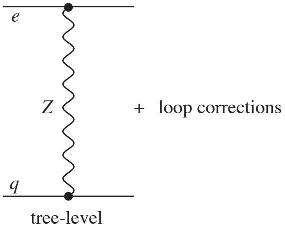
Phys. Rev. D 114 (2026) 1, L011302

Weak charge and atomic parity violation

Nuclear-spin-independent atomic parity violation operator:

$$\hat{W} = \frac{G_F}{2\sqrt{2}} Q_W \, \gamma_5 \rho_N(r)$$

- G_F is Fermi weak interaction constant
- Q_W nuclear weak charge
- ρ_N nuclear density



Observable PNC amplitude in Cs

$$E_{\mathrm{PNC}} = \sum_n \frac{\langle 7s|D|np\rangle\langle np|\hat{W}|6s\rangle}{E_{6s} - E_{np}} + \frac{\langle 7s|\hat{W}|np\rangle\langle np|D|6s\rangle}{E_{7s} - E_{np}}$$

Cesium weak charge: 2σ tension

For $^{133}\mathrm{Cs}$, there is 2σ tension between the radiatively corrected Standard-Model value $Q_W^{(\mathrm{th})}$ and the experimentally measured one $Q_W^{(\mathrm{exp})}$:

Experimental value

$$Q_W^{\mathrm{exp}} = -72.41(42)$$

- Wood C, et al. Science 275:1759 (1997)
- Bennett S, Wieman CE. Phys. Rev. Lett. 82:2484 (1999)

Theoretical value

$$Q_W^{(\mathrm{th})} = -73.26(1).$$

- Marciano, Sirlin, 1983, 1984
- Erler, Ramsey-Musolf, 2005
- Erler, Su, 2013
- Blunden, Melnitchouk, Thomas, 2012
- Dzuba, Flambaum, Sushkov, 1984, 1987, 1989
- Kuchiev, Flambaum, 2002
- Dzuba, Flambaum, Ginges, 2002
- Flambaum, Ginges, 2005
- Porsev, Beloy, and Derevianko, 2009, 2010
- Dzuba, Berengut, Flambaum, Roberts, 2012

Weak mixing angle tension

- At tree level,

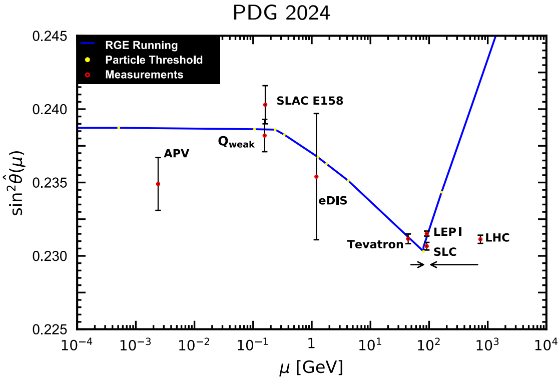
$$Q_W^{(0)} = -N + (1 - 4s_W^2)Z\,, \qquad s_W^2 \equiv \sin^2\theta_W$$

- The radiatively corrected expression used in this work is

$$Q_W^{\rm SM} = -0.98897N + (1.0250 - 3.9978s_W^2)Z.$$

- For $s_W^2 = 0.23873$,

$$Q_W^{\rm SM}({}^{133}\mathrm{Cs}) = -73.26(1).$$



- Marciano–Sanda and Marciano–Sirlin established the $O(\alpha G_F)$ electroweak corrections to atomic weak charges.
- Atomic Breit, QED, correlation, and neutron-skin effects enter the conversion between $E_{\rm PNC}$ and Q_W.
- Blunden–Melnitchouk–Thomas evaluated γZ box/Pauli-blocking correction of order $O(\alpha G_F)$.

Question

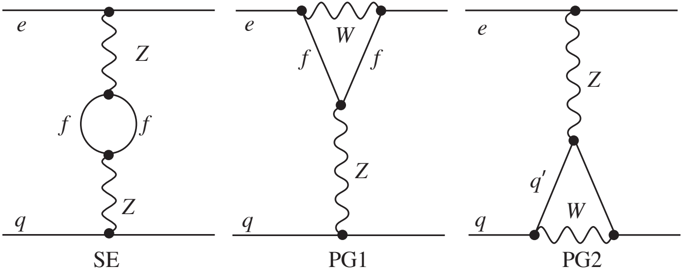
Are there any additional contributions to Q_W of order $O(\alpha G_F)$ which were missed?

Additional contributios to Q_W found in our work

In atomic matrix elements, we have to consider modified operator:

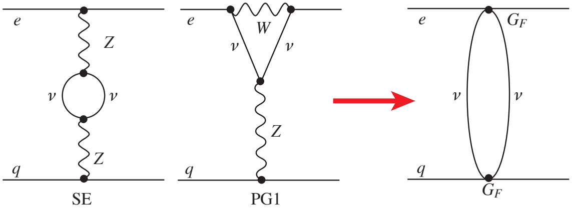
$$W(r) = -\frac{G_F}{2\sqrt{2}}\left(Q_W + \delta Q_W\right)\gamma_5 \rho_N(r)$$

where δQ_W receives contributions from the following diagrams:



Potential due to two-neutrino exchange

At distance $r \gg m_Z^{-1}$, we have two-neutrino exchange:



This diagram creates the effective interaction potential: [Feinberg, Sucher, 1968; 1989; Hsu, Sikivie, 1994]

$$V_{2\nu}(r) \propto \frac{G_F^2}{r^5} \qquad (m_Z^{-1} \ll r \ll m_\nu^{-1})$$

Naively, it is $O(G_F^2)$ and may be neglected.

Why a nominal G_F^2 force can contribute at $O(\alpha G_F)$

- The long-distance potential is valid only for momenta $|q| \ll M_{W,Z}$.
- If it is inserted into an APV matrix element, the radial integral is dominated by its lower limit:

$$4\pi \int_{r_{\min}} dr\, r^2 \frac{G_F^2}{r^5} \sim \frac{G_F^2}{r_{\min}^2}.$$

- The electroweak completion sets $r_{\min} \sim M_Z^{-1}$, hence [M. Ghosh et al. (2025)]

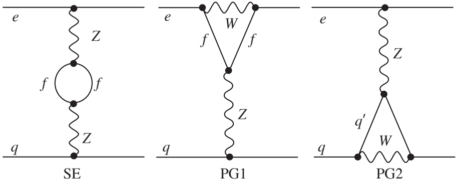
$$\frac{G_F^2}{r_{\text{min}}^2} \sim G_F^2 M_Z^2 \sim \alpha G_F$$

Thus, the two-neutrino exchange creates additional potential which contributes to the atomic matrix elements as $O(\alpha G_F)$ and thus corrects Q_W.

Required calculation

One must replace the four-Fermi vertices by the renormalizable electroweak theory and determine the all-distance potential at $r \sim M_Z^{-1}$. A cutoff imposed directly on the G_F^2/r^5 tail is not a matching calculation.

Calculation of potentials assocuated to the diagrams



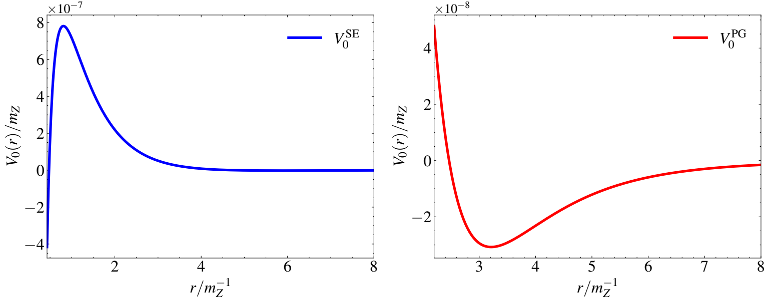
Ghosh et al. (2025) computed the potentials from the discontinuities of the full one-loop amplitudes,

$$V_j(r) = -\frac{1}{4\pi^2 r}\int_0^\infty dt\, \mathrm{Im}\, \mathcal{M}^j_{\mathrm{NR}}(t) e^{-\sqrt{t}r}, \qquad j = \mathrm{SE}, \mathrm{PG}, \mathrm{box}.$$

For electron–quark weak-charge matching, the present work uses SE and PG topologies. Box diagrams are process dependent and are relevant, for example, to electron–electron scattering.

M. Ghosh, Y. Grossman, C. Sieng and B. Yu, Phys. Rev. D 112, 113004 (2025); Phys. Rev. Lett. 135, 251803 (2025). Diagrams above are topology labels, not full Feynman-rule representations.

Potentials



Credit: [M. Ghosh et al Phys.Rev.D 112 (2025) 11, 113004]

These potentials have compact support and may be effectively replaced by the contact interaction in atomic matrix elements!

Aim and calculational statement of the present work

1. Use the all-distance SE and PG potentials of Ghosh et al., including the region $r \sim M_Z^{-1}$.
2. Extend the Z self-energy loop from neutrinos to all fermions with $m_f < M_Z$:

$$\nu_e, \nu_\mu, \nu_\tau; \quad e, \mu, \tau; \quad u, d, s, c, b$$

   with the appropriate chiral $Zf\bar{f}$ couplings and quark colour factors.
3. Integrate each potential to a contact coefficient and match it onto

$$W(r) = -\frac{G_F}{2\sqrt{2}}\,[Q_W + \delta Q_W]\gamma_5 \rho(r).$$

4. Test the resulting shift against Cs APV and low-energy scattering weak charges.

Central claim

The resulting coefficient is numerically of radiative-correction size and shifts the Cs Standard-Model prediction toward the weak charge inferred from the Boulder amplitude.

Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026), Secs. I–III.

Local matching of the short-distance potential

For a potential whose support is short compared with nuclear and electronic scales,

$$V(r) \longrightarrow \kappa\,\delta^3(\boldsymbol{r}), \qquad \kappa = \int d^3r\, V(r).$$

Tree-level Z exchange fixes the normalization:

$$V_Z(r) = -\frac{g^2}{64\pi c_W^2}\frac{e^{-M_Z r}}{r}, \qquad \kappa_Z = -\frac{g^2}{16 c_W^2 M_Z^2}.$$

The correction is extracted from

$$\frac{\langle ns_{1/2}|W_f|n'p_{1/2}\rangle}{\langle ns_{1/2}|W_Z|n'p_{1/2}\rangle} \simeq \frac{\kappa_f}{\kappa_Z}.$$

We find that the relevant integrals converge at $r \lesssim 10/M_Z$;
Electron wave functions and nuclear densities are effectively constant on that matching scale.

Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026), Eq. (1) and Appendix A; M. Ghosh et al., Phys. Rev. D 112, 113004 (2025).

SE contribution: all fermions and quarks contribute except the top

For one massless-neutrino species,

$$\frac{\kappa_{\mathrm{SE}}}{\kappa_Z} = -\frac{g^2}{96\pi^2 c_W^2}.$$

The complete Z self-energy below the top threshold is summarized by

$$N_{\mathrm{eff}} = \frac{160}{3} s_W^4 - 40 s_W^2 + 21 \simeq 14.5.$$

This contains three neutrinos, three charged leptons, and the five light quark flavours with colour and their different left- and right-handed Z couplings. Therefore

Correction due to SE diagram

$$\frac{\delta Q_W^{(\mathrm{SE})}}{Q_W} = -\frac{g^2}{96\pi^2 c_W^2} N_{\mathrm{eff}} = -0.86\%$$

The SE ratio is independent of the vector coupling on the lower external fermion line because that factor is common to the loop and tree amplitudes.

Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026), Eqs. (4)–(5), (38); M. Ghosh et al., Phys. Rev. D 112, 113004 (2025).

PG contribution: small for heavy nuclei, enhanced for the proton

The all-distance triangle potential gives

$$\frac{\kappa_{\rm PG}}{\kappa_Z} \simeq -1.6 \times 10^{-3}.$$

After including the electroweak vertex factors,

$$\frac{\delta Q_W^{(\rm PG)}}{Q_W} = 1.7 \times 10^{-3} \frac{N - Z}{N - (1 - 4s_W^2)Z}.$$

Proton

$$\left.\frac{\delta Q_p}{Q_p}\right|_{\rm PG} \simeq \frac{1.7 \times 10^{-3}}{1 - 4s_W^2} \simeq 3.8\%.$$

Neutron

$$\left.\frac{\delta Q_n}{Q_n}\right|_{\rm PG} \simeq 1.7 \times 10^{-3}.$$

The proton enhancement is entirely due to the small tree-level factor $1 - 4s_W^2 \simeq 0.044$.

Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026), Eqs. (6), (44), (51), (54).

Total correction to nuclear and proton weak charges

Combining SE and PG contributions,

Total correction

$$\frac{\delta Q_W}{Q_W} = \left[-0.86 + 0.17\frac{N-Z}{N-(1-4s_W^2)Z}\right]\%$$

For medium and heavy nuclei,

$$\frac{\delta Q_W}{Q_W} \simeq -0.8\%.$$

Separating proton and neutron density coefficients gives

$$Q_W + \delta Q_W = -0.98207N + (1.0181 - 3.9634s_W^2)Z = -0.98207N + 0.071918Z.$$

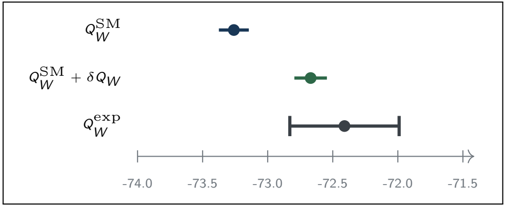
For a free proton, SE and PG combine to

$$\frac{\delta q_W^p}{q_W^p} \simeq +3.0\%.$$

Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026), Eqs. (7)–(9).

Cesium: numerical effect of the additional matching term

$$
\begin{aligned}
Q_W^{\mathrm{SM}} &= -73.26(1), \\
Q_W^{\mathrm{SM}} + \delta Q_W^{\mathrm{SM}} &= -72.67, \\
Q_W^{\mathrm{exp}} &= -72.41(42). \\
\Delta Q_W \text{ before} &= 0.85(42) \quad (2.0\sigma), \\
\Delta Q_W \text{ after} &= 0.26(42) \quad (0.6\sigma).
\end{aligned}
$$



The corresponding Cs extraction becomes

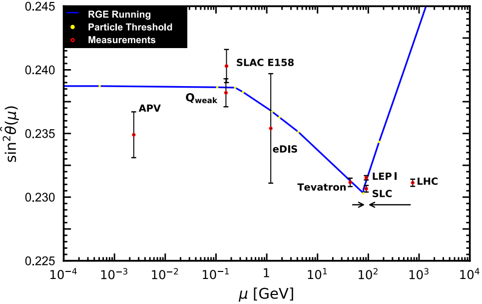
$$\boxed{\sin^2\theta_W(q^2 \simeq 0) = 0.2375(19)}$$

compared with the quoted Standard-Model value 0.23873.

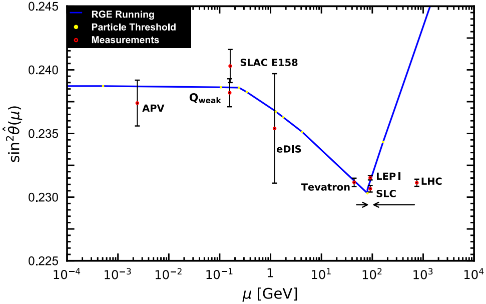
Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026), Eqs. (7), (10) and Sec. III. Error bar in the figure is the quoted 1σ experimental uncertainty.

Weak mixing angle from APV

PDG 2024



Our paper



Stronger bounds on new physics

$$Q_W^{\text{exp}} - (Q_W^{\text{SM}} + \delta Q_W^{\text{SM}}) = 0.26(42)$$

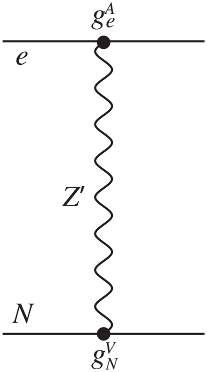
Extra Z' boson:

- For $m_{Z'} \gg \alpha Z m_e$,

$$\frac{|g_e^A g_N^V|}{m_{Z'}^2} < 2.2 \times 10^{-8}\ \text{GeV}^{-2}$$

- For $m_{Z'} \ll 1/R_{\text{atom}}$

$$|g_e^A g_N^V| < 1.7 \times 10^{-14}$$



Conclusions

- The precision Cs observable is the 1997 ratio E_{PNC}/β; historical changes in Q_W primarily reflect changes in β, k_{PNC}, and electroweak/nuclear inputs.
- The PDG-style extraction adopted in this work gives $Q_W^{\mathrm{exp}} = -72.41(42)$, differing by 2.0σ from the baseline $Q_W^{\mathrm{SM}} = -73.26(1)$.
- The G_F^2/r^5 four-Fermi potential is ultraviolet sensitive in APV. Its electroweak completion generates a contact coefficient of order $G_F^2 M_Z^2 \sim \alpha G_F$.
- Using the all-distance SE and PG potentials and including all light fermions in the SE loop gives

$$\delta Q_W/Q_W \simeq -0.8\% \quad \text{for Cs}, \qquad \delta Q_W^p/Q_W^p \simeq +3.0\%.$$

- The shifted Cs prediction, -72.67, differs from the adopted extraction by $0.26(42)$.
- The finite-nuclear-size versus short-distance-matching issue remains a substantive theoretical point requiring an operator-level comparison.

K. S. Kumar et al., Annu. Rev. Nucl. Part. Sci. 63, 237 (2013); M. Ghosh et al., Phys. Rev. D 112, 113004 (2025); Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026).

Backup

The experiment does not measure Q_W directly

The $6S_{1/2} \to 7S_{1/2}$ parity-violating amplitude is written as

$$\mathrm{Im}\, E_{\mathrm{PNC}} = \frac{Q_W}{N}\, k_{\mathrm{PNC}}.$$

The Boulder experiment measured

$$\frac{\mathrm{Im}\, E_{\mathrm{PNC}}}{\beta} = 1.5935(56)\ \mathrm{mV/cm}, \qquad \text{relative uncertainty } 0.35\%,$$

where β is the vector transition polarizability. The weak charge follows from

$$Q_W = \left(\frac{E_{\mathrm{PNC}}/\beta}{M_{\mathrm{hf}}/\beta}\right)\left(\frac{N M_{\mathrm{hf}}}{k_{\mathrm{PNC}}}\right).$$

Direct observable

E_{PNC}/β

Atomic calibration

β or M_{hf}/β

Theory input

k_{PNC}, neutron density, electroweak matching

C. S. Wood et al., Science 275, 1759 (1997); K. S. Kumar et al., Annu. Rev. Nucl. Part. Sci. 63, 237 (2013), Sec. 3.1.

Historical overview: relativistic many-body calculations

1984–1992: calculation of the Cs PNC amplitude

- **Dzuba–Flambaum–Sushkov (1984–1989):** the estimated accuracy of relativistic calculations of the $6s \to 7s$ amplitude improved from $\sim 3\%$ to $\sim 2\%$ and then to $< 1\%$. The 1989 calculation summed to all orders the dominant correlation chains: Coulomb screening, hole–particle interaction, and iterations of the correlation potential Σ through a Dyson equation, using relativistic Hartree–Fock orbitals and Green functions.
- **Blundell–Johnson–Sapirstein (1990–1992):** independent high-accuracy calculations confirmed the result at the $\sim 1\%$ level.

1997–2000: Stark calibration and the first Cs tension

- **Wood et al.** measured $\mathrm{Im}\, E_{\mathrm{PNC}}/\beta$ with 0.35% uncertainty. Bennett–Wieman measured $M1_{\mathrm{hfs}}/\beta$ and obtained

$$\beta = 27.024(43)_{\mathrm{exp}}(67)_{\mathrm{th}}\, a_0^3, \qquad Q_W = -72.06(28)(34),$$

corresponding to the then 2.3σ tension with the Standard Model.
- **Dzuba–Flambaum (2000):** calculated $M1_{\mathrm{hfs}}$ to 0.1% and showed that its square-root scaling, combined with the measured $6s$ and $7s$ hyperfine constants, calibrates β.

Dzuba–Flambaum–Silvestrov–Sushkov, Phys. Lett. A 103, 265 (1984); J. Phys. B 20, 1399 (1987); Dzuba–Flambaum–Sushkov, Phys. Lett. A 141, 147 (1989); Blundell–Johnson–Sapirstein, Phys. Rev. Lett. 65, 1411 (1990); Blundell–Sapirstein–Johnson, Phys. Rev. D 45, 1602 (1992).
Wood et al., Science 275, 1759 (1997); Dzuba–Flambaum–Sushkov, Phys. Rev. A 56, R4357 (1997); Bennett–Wieman, Phys. Rev. Lett. 82, 2484 (1999); Dzuba–Flambaum, Phys. Rev. A 62, 052101 (2000).

Historical overview: QED corrections and Cs re-evaluations

2001–2005: radiative corrections to the PNC amplitude

- **Weak matrix element (2001–2003):** the Uehling contribution is $+0.40\%$, while the strong-field electron-line correction (self-energy plus vertex) is $\Delta_{\mathrm{SE+V}} = -0.73(20)\% \simeq -0.8\%$. This short-distance correction changes the $s_{1/2}$ and $p_{1/2}$ wave functions in the weak matrix element and removes the apparent conflict with the Standard Model. The complete calculation was reviewed by Kuchiev–Flambaum.
- **Full many-electron QED result (2005):** Flambaum–Ginges found

$$\Delta_{\mathrm{energies}} = -0.34\% \qquad \Delta_{\mathrm{E1}} = +0.43\%$$
$$\Delta_{\mathrm{weak}} = -0.41\% \qquad \Delta E_{\mathrm{PNC}} = (-0.32 \pm 0.03)\%$$

2010–2012: later many-body re-evaluations

- **2010, coupled-cluster triples:** $k_{\mathrm{PNC}} = 0.8906(26)$ and $Q_W = -73.16(28)(20)$, in agreement with the Standard Model.
- **2012, core–tail re-evaluation:** $k_{\mathrm{PNC}} = 0.8977(40)$ confirmed the earlier all-order result 0.8980(45) rather than introducing a new QED correction; the inferred value was $Q_W = -72.58(43)$, 1.5σ from $Q_W^{\mathrm{SM}} = -73.24(5)$.

Johnson–Bednyakov–Soff, Phys. Rev. Lett. 87, 233001 (2001); Dzuba–Flambaum–Ginges, Phys. Rev. D 66, 076013 (2002); Kuchiev–Flambaum, Phys. Rev. Lett. 89, 283002 (2002), J. Phys. B 36, R191 (2003) [hep-ph/0305053]; Flambaum–Ginges, Phys. Rev. A 72, 052115 (2005) [physics/0507067].
Porsev–Beloy–Derevianko, Phys. Rev. Lett. 102, 181601 (2009); Phys. Rev. D 82, 036008 (2010); Dzuba–Berengut–Flambaum–Roberts, Phys. Rev. Lett. 109, 203003 (2012).

Historical overview of theoretical calculations

Year	Analysis	$k_{\rm PNC}/(10^{-11} ea_0)$	Extracted $Q_W(^{133}\rm Cs)$	Comparison with the SM used then
1999	Bennett–Wieman	0.9065(36)	$-72.06(28)_{\rm exp}(34)_{\rm th}$	2.3σ deviation
2010	Porsev–Beloy–Derevianko; coupled cluster with triples	0.8906(26)	$-73.16(28)(20)$	agreement
2012	Dzuba–Berengut–Flambaum–Roberts reevaluation	0.8977(40)	$-72.58(43)$	1.5σ vs. $-73.24(5)$

Interpretation

The movement of the central value from 1999 to 2012 was generated mainly by changes in $k_{\rm PNC}$ and electroweak/nuclear corrections, not by a new measurement of $E_{\rm PNC}/\beta$.

S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. 82, 2484 (1999); S. G. Porsev et al., Phys. Rev. D 82, 036008 (2010); V. A. Dzuba et al., Phys. Rev. Lett. 109, 203003 (2012); K. S. Kumar et al., Annu. Rev. Nucl. Part. Sci. 63, 237 (2013).

Post-2013 experimental updates concern auxiliary atomic inputs

Year	Quantity	Result and relevance
2019	Sum-over-states determination of β	$\beta = 27.139(42)$ a.u.; shifted the inferred weak charge and disagreed with the earlier $M1/\beta$ determination.
2023	Reevaluation of the same method	$\beta = 26.887(38)$ a.u.; recommended average $\beta = 26.912(30)$ a.u., restoring consistency with the $M1/\beta$ route.
2024	Direct measurement of α/β	$\alpha/\beta = -9.902(9)$; confirms the previous ratio but does not remeasure the parity-violating amplitude.
2024	Precision dc Stark shift	Derived $\widetilde{\beta} = 27.043(36)$ a.u.; provides an additional calibration constraint.

Status through 2026

Wood et al. remains the direct E_{PNC}/β input used in precision Cs weak-charge extractions. Later measurements refine β, dipole matrix elements, and related atomic quantities.

G. Toh et al., Phys. Rev. Lett. 123, 073002 (2019); H. B. Tran Tan et al., Phys. Rev. A 108, 022808 (2023); J. A. Quirk et al., Phys. Rev. A 109, 062809 (2024); J. A. Quirk et al., Phys. Rev. Lett. 132, 233201 (2024).

Low-energy scattering weak charges

Proton

Using $Q_W^{p,\mathrm{SM}} = 0.06987(50)$,

$$Q_W^{p,\mathrm{SM}} + \delta Q_W^{p,\mathrm{SM}} = 0.06987(1 + 0.03) = 0.0719,$$

in numerical agreement with the Qweak result

$$Q_W^{p,\mathrm{exp}} = 0.0719(45).$$

Electron

The same $(1 - 4s_W^2)^{-1}$ enhancement occurs for the electron weak charge in low-energy Møller scattering. The paper states that the correction can be at the several-percent level, but does not calculate it.

The corrected Cs residual also gives

$$\frac{|g_e^A g_N^V|}{m_{Z'}^2} < 2.2 \times 10^{-8}\ \mathrm{GeV}^{-2}, \qquad S = -0.32(53)$$

under the assumptions stated in the article.

Qweak Collaboration, Nature 557, 207 (2018); SLAC E158 Collaboration, Phys. Rev. Lett. 95, 081601 (2005); Flambaum and Samsonov, Phys. Rev. D 114, L011302 (2026), Sec. III.