

Effects of dispersion parity-violating interaction in electron scattering and atoms

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(Received 15 March 2026; accepted 11 June 2026; published 6 July 2026)

Exchange of two neutrinos (as well as other fermions) generates a long-range parity-violating potential of the form $\sim G^2/r^5$, with characteristic range $\hbar/(2m_\nu c)$. In atomic systems the corresponding matrix elements converge at distances $r < 10/M_Z$, so that the interaction between electron and quarks effectively reduces to a contact term $\sim G^2 M_Z^2 \delta^3(\vec{r}) \sim G\alpha\delta^3(\vec{r})$. This interaction produces a -0.8% correction to the effective weak charge of cesium, resolving the 2σ discrepancy between the Standard Model prediction and the measured Cs parity-violation amplitude. The corresponding value of the weak mixing angle is $\sin^2 \theta_W = 0.2375(19)$ at $q^2 \approx 0$, in agreement with the Standard Model prediction $\sin^2 \theta_W = 0.23873$. The relative correction to the proton weak charge is about 3%. Using these results, we revisit the limits on an additional Z' boson and obtain a constraint on isospin-conserving oblique radiative corrections characterized by the Peskin–Takeuchi parameter $S = -0.32(53)$ at $q^2 \approx 0$.

DOI: [10.1103/cb8l-bt9n](https://doi.org/10.1103/cb8l-bt9n)

Introduction. Exchange of two neutrinos as in Fig. 1 produces long-range potential $\propto G^2/r^5$ in the particle interaction, where G is the Fermi constant [1–5]. The effects of the parity-conserving part of this potential are, however, many orders of magnitude smaller than the sensitivity of the experiments [6–13] and are practically unobservable.

In Refs. [14–18] it was noted that the neutrino exchange potential has a parity violating (PV) part $\propto G^2/r^5$ with the range $\hbar/2m_\nu c$ exceeding atomic size by several orders of magnitude. It was also demonstrated that mixed γZ electron vacuum polarization produces PV potential $\propto \alpha G/r^3$ with the range $\hbar/2m_e c = 193$ fm, which exceeds the range of the weak interaction by five orders of magnitude [14,16], similar to the range of the Uehling potential due to electron vacuum polarization by the nuclear Coulomb field.

Although the long-distance behavior of the PV potential proportional to G^2/r^5 was accurately calculated in Refs. [14–16], obtaining a reliable numerical estimate of the effect produced by this potential requires regularization of the singular PV interaction at short distances. In Ref. [16], this was achieved by introducing the Z -boson mass into the integral describing the long-range PV

potential. While this procedure provided a reasonable numerical estimate of the effect, no actual calculation of the short-distance PV potential was performed. Therefore, the result of Ref. [16] should be regarded as an estimate rather than a fully accurate calculation.

The authors of Refs. [17,18] showed that the neutrino-exchange potential significantly affects PV matrix elements in muonium, positronium, and atoms. In particular, the PV matrix element in the Cs atom changes by $\sim -0.3\%$, improving the agreement of the Standard Model (SM) prediction with experiments [19]. In the present letter, we extend this analysis by including the contributions of other fermions in the loop.

The contribution of the diagrams in Fig. 1 with exchange by two neutrinos and by other fermions to the PV effects in atoms is $\sim 1\%$, and this significantly exceeds the error 0.35% of the PV measurement in the Cs atom [19] and the error $< 0.5\%$ in the many-body atomic calculations of the Z -boson contribution [20–27]. The work is in progress to improve both experimental [28–30] and theoretical [31] accuracy.

The error in atomic calculations cancels out in the ratio of the PV amplitudes in different isotopes of the same atom [32–34]. The measurement for the chain of isotopes of the Yb atom was performed in Ref. [35].

The study of PV in atoms provides high precision tests of the Standard Model and new physics beyond it [36,37].

We will also show that the diagrams on Fig. 1 give significant contributions to the PV effects in low-energy scattering of electron from proton, deuteron, and other nuclei. The corresponding corrections to the proton and nuclear weak charges are found. A significant correction to

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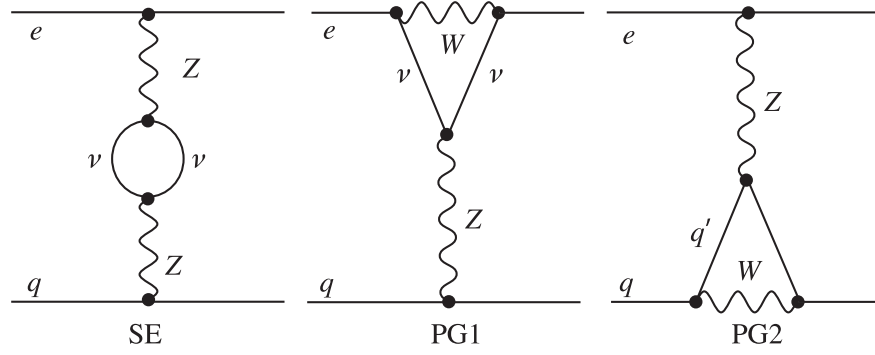


FIG. 1. Feynman diagrams contributing to the long-range force due to neutrino exchange between electron e and quark q . The self-energy (SE) diagram may also contain other leptons and quarks in the loop while the “penguin” (PG1) diagram has only the electronic neutrino in the loop.

PV effects in electron-electron scattering and to the electron weak charge is also expected, but it will be studied elsewhere.

Weak charge Q_W is the constant of the electron-nucleon weak interaction due to the Z -boson exchange which has interaction range $r_Z = \hbar/M_Z c \approx 0.002$ fm. On the nuclear and atomic scales this may be considered as a Fermi-type contact interaction.

Radiative corrections to the proton and neutron weak charges of the order $\alpha \approx 1/137$ have been calculated in Refs. [38–42] and were shown to exceed 1%. However, diagrams on Fig. 1, which actually give comparable contributions, have not been included into these calculations. The point is that at large distance these diagrams give interaction proportional to G^2 , which is very small. However, this interaction is highly singular, $\propto G^2/r^5$, and integration over distance with electron wave functions and effective cutoff at $r \sim 1/M_Z$ gives contribution $\sim G^2 M_Z^2 \sim \alpha G$. Thus, the suppression relative to the ordinary weak interaction mediated by the Z -boson exchange is $\sim \alpha$ [16].

For electron-electron scattering there are also box diagrams with crossing electron and crossing neutrinos lines. Note that in the case of Majorana neutrinos, there is an additional box diagram with neutrinos as the vertical sides. Potentially, this could give a possibility to identify Majorana neutrinos using PV in electron scattering, but the contribution of this diagram is small.

To perform accurate calculations, we require the effective potential generated by the diagrams shown in Fig. 1 at distances $r \sim 1/M_Z$. The neutrino-exchange contribution to this potential, valid for all distances satisfying $r \ll 1/m_\nu$, was calculated in Refs. [17,18], and our analysis is based on these results. We further include the additional contributions arising from other fermions in the loop.

In this letter, we use natural units with $\hbar = c = 1$.

Effective potential due to the fermion loop. Parity violating interactions produce PV effects in atoms by mixing $s_{1/2}$ and

$p_{1/2}$ electron orbitals. To find corrections produced by diagrams on Fig. 1 it is sufficient to calculate the ratio of the matrix elements

$$\frac{\langle ns_{1/2} | W_f(r) | n' p_{1/2} \rangle}{\langle ns_{1/2} | W_Z(r) | n' p_{1/2} \rangle}, \quad (1)$$

where W_Z and W_f are the PV potentials produced by Z boson tree-level exchange and f fermion loop correspondingly.

Dominating contribution to both matrix elements comes from the distance between electron and quark of order $r \sim 1/M_Z$, which is very small as compared to the scale of the variation of electron wave functions and nuclear size. Therefore, we may replace both potentials by their Fermi-type contact approximations $w_{Z,f} \delta^3(\vec{r})$ using relation $\int W_{Z,f}(r) 4\pi r^2 dr = w_{Z,f} \int \delta^3(\vec{r}) d^3 r$. Then the nuclear-spin-independent part of the electron-nucleus PV operator $W(r)$ may be cast in the form

$$W(r) = -\frac{G}{2\sqrt{2}} (Q_W + \delta Q_W) \gamma_5 \rho(r), \quad (2)$$

where $Q_W = -N + (1 - 4 \sin^2 \theta_W)Z$ is the weak nuclear charge, δQ_W is the correction produced by the diagrams on Fig. 1, $\rho(r)$ is the nuclear density normalized by the condition $\int \rho(r) d^3 r = 1$, and N and Z are numbers of neutrons and protons in the nucleus, respectively. Inclusion of radiative corrections gives [43,44]

$$\begin{aligned} Q_W &= -0.98897N + (1.0250 - 3.9978 \sin^2 \theta_W)Z \\ &= -0.98897N + 0.070605Z. \end{aligned} \quad (3)$$

For cesium atom, this formula implies the standard model value of the weak charge $Q_W^{\text{SM}} = -73.26(1)$ assuming $\sin^2 \theta_W = 0.23873$ at zero momentum transfer [44]. The experimental measurements of the parity violation in cesium atom give $\sin^2 \theta_W = 0.2349(18)$ at $q = 2.4$ MeV [44].

Note that the differences in the experimental values of Cs weak charge and Weinberg angle in 2024 and 2022 editions of Particle Data group reviews are due to the different values of the Stark polarizability β used (Cs PV experiment measures ratio of the PV amplitude to β). The 2023 paper [45] corrected the result of Ref. [46] and confirmed the original value of β found in our paper [47].

Calculations of the neutrino exchange potentials, presented in Supplemental Materials [48], are similar to that described in detail in Ref. [17]. Let us start from the SE diagram in Fig. 1. The interaction constant on the bottom fermion line cancels with the single Z-boson exchange contribution in the ratio (1). Therefore, for any fermion on the bottom line (e.g., quark or electron in the low-energy electron-electron scattering case) the ratio of the SE diagram to the tree-level Z-boson contribution is the same. As a result we obtain

$$\frac{\delta Q_W^{(\text{SE})}}{Q_W} = -\frac{g^2}{96\pi^2 c_W^2} N_{\text{eff}} = -0.86\%, \quad (4)$$

where $g \approx 0.65$ is the Z-boson-neutrino interaction constant, $c_W^2 = 1 - s_W^2 = 0.76127$, $s_W^2 \equiv \sin^2 \theta_W$. Following Refs. [11,16], we introduced here effective number of neutrinos,

$$N_{\text{eff}} \approx 14.5. \quad (5)$$

Indeed, there are three ordinary neutrinos. However, we should add one-loop contributions of all fermions with masses smaller than that of the Z-boson, including $e, \mu, \tau, u, d, s, c, b$. N_{eff} is not an integer number since interaction constants of other fermions with Z-boson are different from that for neutrinos, see Supplemental Materials [48] for details.

Diagrams PG1 and PG2 in Fig. 1 do not have enhancement factor N_{eff} . Using the calculations of the momentum and radial integrals presented in the Supplemental Materials [48], we obtain the following correction to the nuclear weak charge:

$$\frac{\delta Q_W^{(\text{PG})}}{Q_W} = 1.7 \times 10^{-3} \frac{N - Z}{N - (1 - 4s_W^2)Z}. \quad (6)$$

For the proton weak charge this ratio, enhanced by the small value of $(1 - 4\sin^2 \theta_W) = 0.044$ in the denominator, is 3.8%. Adding contribution (4) corresponding to the SE diagram, we obtain the total correction to the nuclear weak charge

$$\frac{\delta Q_W}{Q_W} = \left(-0.86 + 0.17 \frac{N - Z}{N - (1 - 4s_W^2)Z} \right) \%. \quad (7)$$

Equation (7) shows that the contribution of the diagrams PG1 and PG2 (given in the last term) for all atoms, except

for hydrogen, is small, so we obtain $\delta Q_W / Q_W \approx -0.8\%$ in all medium and heavy atoms. For the proton weak charge this gives,

$$\frac{\delta q_W^p}{q_W^p} \approx 3.0\%. \quad (8)$$

Similar relative correction to the PV effect in muonium atom was obtained in Refs. [17,18], where the authors do not interpret this as a correction to the weak charge.

The enhancement due to the small value of $(1 - 4s_W^2)$ in the denominator is also expected for the electron weak charge in the low-energy parity-violating electron-electron scattering. Therefore, the relative correction to the electron weak charge may exceed 1%.

Distribution of proton and neutron densities in the nucleus are slightly different. Therefore to take into account this effect in numerical calculations it may be convenient to separate proton and neutron contributions to the weak charge. Adding the corrections (7) to Eq. (3) we find

$$\begin{aligned} Q_W + \delta Q_W &= -0.98207N + (1.0181 - 3.9634s_W^2)Z \\ &= -0.98207N + 0.071918Z. \end{aligned} \quad (9)$$

Here we assume the SM value of the Weinberg angle with $\sin^2 \theta_W = 0.23873$ at zero momentum transfer [44].

Recall that the aim of the present paper is to calculate the contribution of the PV potential to the effective weak charge in Eq. (2) which includes the nuclear density function $\rho(r)$. This function, however, drops out from the ratio of the PV potential contribution to the standard Z-boson contribution $\delta Q_W / Q_W$. Calculations of atomic matrix elements of the potential $W(r)$ in Eq. (2) performed in previous works [20–27] do take into account of $\rho(r)$, which is usually described by a Fermi-type distribution fitted to measured proton and neutron densities. Understanding that the effects of the nuclear density distribution have been fully addressed in these papers, we do not need to consider them here.

Comparison with experimental data on weak charges and limits on new physics. If we use the value of the proton weak charge obtained in the recent very accurate lattice calculation [49], $Q_W^{\text{SM}} = 0.06987(50)$, we obtain corrected value $Q_W^{\text{SM}} + \delta Q_W^{\text{SM}} = 0.06987(1 + 0.03) = 0.0719$. It agrees with $Q_W^{\text{exp}} = 0.0719(45)$ measured by Qweak Collaboration [50].

The correction to the electron weak charge is also expected at the level of several percent. This does not contradict to the experimental value of the electron weak charge $Q_W^{\text{exp}} = -0.053(11)$ obtained by E158 Collaboration [51]. The accuracy in the experimental measurement of the proton weak charge in the electron-proton scattering by Qweak Collaboration is 7%, the accuracy in the measurement of the PV asymmetry in electron-electron

scattering by E158 Collaboration is 20%. However, both experimental collaborations are expecting significant improvements of the accuracy soon.

The most sensitive point to the weak charge correction is currently in cesium PV experiments, where $\delta Q_W/Q_W \approx -0.8\%$ exceeds both the experimental error 0.35% and the error in our atomic many-body calculation which is under 0.5%. This correction actually eliminates 2σ difference between the measured $Q_W^{\text{exp}} = -72.41(42)$ and the standard model $Q_W^{\text{SM}} + \delta Q_W^{\text{SM}} = -73.26(1 - 0.008) = -72.67$ weak charges.

After including δQ_W^{SM} , the measured in Cs PV experiment value of the Weinberg angle at $q^2 \approx 0$, corresponding to

$$\sin^2 \theta_W = 0.2375(19), \quad (10)$$

also comes to a perfect agreement with prediction of the Standard Model $\sin^2 \theta_W = 0.2387$.

The difference $Q_W^{\text{exp}} - (Q_W^{\text{SM}} + \delta Q_W^{\text{SM}}) = 0.26(42)$ allows us to obtain limits on new physics. The limits on the additional Z' -boson interaction strength obtained as a function of Z' mass from the measurements of PV in Cs atom are approximately two times stronger than that presented in Table II and Fig. 1 of Ref. [52]. For $m_{Z'} \gg \alpha Z m_e$, the products of Z' interaction constants with the electron and nucleus obeys the following bound: $|g_e^A g_N^V|/m_{Z'}^2 < 2.2 \times 10^{-8} \text{ GeV}^{-2}$. For $m_{Z'} \ll 1/R_{\text{atom}}$, the product of these constants is limited by $|g_e^A g_N^V| < 1.7 \times 10^{-14}$.

We also obtain limits on oblique radiative corrections produced by new particles. Reference [53] calculated the shift of the weak charge produced by these corrections $\Delta Q_W = -0.8S$, where S is the Peskin–Takeuchi parameter characterizing isospin-conserving vacuum-polarization effects. Comparing this expression with the measured value $\Delta Q_W = 0.26(42)$, we obtain

$$S = -0.32(53). \quad (11)$$

The global electroweak fit of S [44] is dominated by the Z -pole and W -mass measurements, while atomic PV probes oblique radiative corrections at very low momentum transfer, $q^2 \approx 0$, thereby testing their running over a wide

range of scales. Light weakly interacting states can induce momentum-dependent vacuum-polarization effects that contribute differently at $q^2 \approx 0$ and $q^2 \sim m_Z^2$. In this case, PV in cesium provides sensitivity to new physics effects that may not be fully captured by high-energy fits.

Thus the approach of Ref. [54] describes the coherent elastic electron-nucleus component of the finite-size potential, whereas the correction discussed here is the short-distance radiative correction to the local weak charge.

Note added. After completion of this work and presenting our results in arXiv, Gorchtein and Spiesberger [54] argued that the two-neutrino-exchange contribution to atomic parity violation in ordinary atoms is eliminated, for practical purposes, by finite nuclear-size effects. We disagree with using the coherent nuclear elastic form factor as an ultraviolet cutoff on the electroweak loop before the short-distance matching is performed. The contribution considered in the present work is a radiative correction to the pointlike Standard Model electron-fermion amplitude, matched at virtual momenta of order M_Z onto local parity-violating electron–quark operators. Nuclear structure enters only subsequently, through matrix elements of these local quark currents, equivalently through the proton and neutron density distributions in the atomic problem. Multiplying the loop amplitude by the nuclear form factor from the outset (effectively using nuclear radius as a short distance cutoff) treats the nucleus as a smooth elementary source at distances at which the loop resolves its constituents, and therefore removes the short-distance Wilson coefficient generated by pointlike electron-quark interactions. In our treatment finite nuclear size smears the resulting contact interaction over the nuclear density, but does not replace the short-distance scale by the nuclear radius. This is the origin of the difference between the conclusion of Ref. [54] and the result obtained here.

Acknowledgments. The work was supported by the Australian Research Council Grant No. DP230101058.

Data availability. There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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