CP-violating electron-nucleon interactions from leptoquark exchange

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(Received 7 August 2003; published 17 December 2003; corrected 23 January 2004)

We investigate the *CP*-violating electron-quark interactions arising from the exchange of spin-1 and spin-0 leptoquarks coupled to the first fermion family and deduce the bounds on the *CP*-violating products of the effective leptoquark-fermion coupling constants from experimental limits on *CP*-violating electron-nucleon interactions.

DOI: 10.1103/PhysRevD.68.116004 PACS number(s): 11.30.Er, 12.60.−i, 14.80.−j, 32.10.Dk

I. INTRODUCTION

CP violation [1] has been seen in the mixing of neutral kaons and recently also in the $K^0 \to 2\pi$ amplitudes [2] and in the decays of neutral *B* mesons [3]. The experimental information is consistent with the most economical possibility, that the observed effects are due to the Kobayashi-Maskawa phase δ_{KM} [4] in the standard model (SM) [5]. A major question in the field of *CP* violation is whether there are sources of *CP* violation other than δ_{KM}, independently of their relevance, or lack of it, for the observed *CP* violation. A further source of *CP* violation in the SM is the θ term in the QCD Lagrangian. New sources of *CP* violation are present in many extensions of the SM. It is relevant to mention in this connection that δ_{KM} is not sufficient to generate the baryon asymmetry of the Universe [6]. The most suitable observables to probe the existence of new *CP*-violating interactions are those for which the contribution from δ_{KM} is small.

In this paper we shall be concerned with electron-quark (e-q) interactions that violate both *CP* and *P* (referred to for brevity as CPV e-q interactions in the following) [7]. Stringent limits on the strength of such interactions come from searches for electric dipole moments (EDMs) of atoms, and the parity- (*P*) and time-reversal- (*T*) violating nuclear spin-flip parameter ν in molecules [8]. The CPV e-q interactions contribute to these observables through CPV electron-nucleon (e-N) interactions, which they induce. The CPV e-N interactions given rise to by δ_{KM} are very weak, with a strength of $\sim 10^{-16} G_F$ (G_F = Fermi constant), since they appear only in second order in the weak interaction [9]. For comparison, current experiments probe CPV e-N interactions at the level of $\sim 10^{-7} G_F$ (see Sec. II). The contribution of the θ term is also small, of strength $\lesssim 10^{-10} G_F$ [9]. The CPV e-N interactions can be much stronger, however, in some extensions of the SM. CPV e-q interactions have been studied in multi-Higgs-boson models [9–11], leptoquark models [11,9,12], and in the *R*-parity-conserving [13] and the R-parity-violating minimal supersymmetric standard model [14]. CPV e-q interactions for the *s* quark have been analyzed in Ref. [15].

The aim of this paper is to deduce the information on the *CP*-violating effective leptoquark-fermion coupling constants (see Sec. III) provided by experimental bounds on CPV electron-nucleon interactions [16]. We investigate both spin-1 and spin-0 leptoquarks (LQs) and consider also contributions that arise from the mixing of LQs of definite SM coupling constants. Spin-1 and spin-0 LQ exchange as possible sources of CPV e-q interactions were noted first in Ref. [11]. Further previous work on CPV e-q interactions from LQ exchange is contained in Refs. [9] and [12], where the contribution of spin-0 LQs was considered in the absence of LQ mixing.

In the next section we consider the nucleon matrix elements of the scalar, pseudoscalar, and tensor quark currents and, using the results of atomic calculations, present the bounds on the coupling constants of the CPV interaction from atomic EDMs and the molecular parameter ν(TlF). In Sec. III we identify the contributions of LQs coupled to the first fermion family to the CPV e-q interactions and deduce the limits on the CPV products of the effective LQ-fermion coupling constants. We consider then some other contributions of these coupling constants. In Sec. IV we summarize our conclusions.

II. BOUNDS ON *CP*-VIOLATING *e*-*u* AND *e*-*d* INTERACTIONS

The most general form of the CPV e-N interaction, including nonderivative couplings only, is given by [7]

$$H_{eN} = \sum_{a=p,n} \frac{G_F}{\sqrt{2}} (k_{Sa} \bar{e} i \gamma_5 e \bar{a} a + k_{Pa} \bar{e} e \bar{a} i \gamma_5 a + k_{Ta} \bar{e} i \gamma_5 \sigma_{\mu\lambda} e \bar{a} \sigma^{\mu\lambda} a), \tag{1}$$

where k_{Sa}, k_{Pa}, and k_{Ta} are real constants [17]. The interaction (1) violates also time-reversal invariance and (automatically) invariance under parity [18]. It contributes therefore to observables that are both parity and time-reversal violating (*P*, *T* violating), such as the EDMs. Stringent bounds on the interaction (1) are set by the experimental limits

$$|d(\mathrm{Tl})| < 9.4 \times 10^{-25} \ e\,\mathrm{cm} \quad (90\% \ \mathrm{C.L.}), \tag{2}$$

$$|d(\mathrm{Cs})| < 1.5 \times 10^{-23} \ e\,\mathrm{cm} \quad (90\% \ \mathrm{C.L.}), \tag{3}$$

$$|d(\mathrm{Hg})| < 2.1 \times 10^{-28} \ e\,\mathrm{cm} \quad (95\% \ \mathrm{C.L.}), \tag{4}$$

$$|d(\mathrm{Xe})| < 6 \times 10^{-27} \ e\,\mathrm{cm} \quad (95\% \ \mathrm{C.L.}), \tag{5}$$

$$|\nu(\mathrm{TlF})| < 4 \times 10^{-4} \ \mathrm{Hz} \quad (90\% \ \mathrm{C.L.}), \tag{6}$$

on the EDM of the ^{205}Tl [19], ^{133}Cs [20], ^{199}Hg [21], and ^{129}Xe [22] atoms and on the P, T-violating spin-flip parameter ν(TlF) of the TlF molecule [23].

Atomic physics calculations yielded the following results for the contribution of the interaction (1) to the above observables [7]:

$$d(\mathrm{Tl}) \simeq 6.9\times 10^{-18}[(0.4k_{Sp}+0.6k_{Sn})-10^{-3}k_{Tp}]e\ \mathrm{cm}, \tag{7}$$

$$d(\mathrm{Cs}) \simeq -7.1\times 10^{-19}[(0.4k_{Sp}+0.6k_{Sn}) + 1.3\times 10^{-2}k_{Tp}]e\ \mathrm{cm}, \tag{8}$$

$$d(\mathrm{Hg}) \simeq -2.0\times 10^{-20}[k_{Tn}+3\times 10^{-3}k_{Pn} + 3\times 10^{-2}(0.4k_{Sp}+0.6k_{Sn})]e\ \mathrm{cm}, \tag{9}$$

$$d(\mathrm{Xe}) \simeq -4.1\times 10^{-21}[(0.24k_{Tp}+0.76k_{Tn}) + 2.4\times 10^{-3}(0.24k_{Pp}+0.76k_{Pn}) + 10^{-2}(0.4k_{Sp}+0.6k_{Sn})]\ \ e\ \mathrm{cm}, \tag{10}$$

$$\nu(\mathrm{TlF}) \simeq -900[(0.75k_{Tp}+0.25k_{Tn}) + 1.5\times 10^{-3}(0.75k_{Pp}+0.25k_{Pn}) + 2.6\times 10^{-2}(0.4k_{Sp}+0.6k_{Sn})]\ \ \mathrm{Hz}. \tag{11}$$

The relative suppression of the tensor contribution in d(Tl) and d(Cs) is due to the enhancement of the scalar contribution by factors of Z ($\equiv$ atomic number) and N ($\equiv$ number of neutrons). In d(Tl) the tensor contribution is anomalously small [an order of magnitude smaller than in d(Cs)], due to cancellations [7]. The pseudoscalar contribution is suppressed relative to the tensor contribution by about three orders of magnitude [and is therefore neglected in d(Tl) and d(Cs)], since it arises as a correction to the nonrelativistic approximation for the nucleons. The contribution of the scalar interaction appears in all cases through the same combination of k_{Sp} and k_{Sn}. This is due to the approximate equality of the ratio Z/N for the nuclei involved. In ^{199}Hg, ^{129}Xe, which are diamagnetic atoms, and also in TlF, the contribution of the scalar interaction is suppressed by about two orders of magnitude relative to the tensor contribution, since it can contribute only through the intervention of the hyperfine interaction [7].

Our interest will be in the implications of the experimental limits (2)–(6) on the CPV e-q interactions, which induce the CPV e-N interaction. In the following we shall restrict our attention to e-u and e-d interactions, as appropriate for leptoquarks coupled to the first fermion family. The most general nonderivative CPV e-u and e-d interaction has the same structure as the e-N interaction (1) [7]:

$$H_{eq} = \sum_{q=u,d} \frac{G_F}{\sqrt{2}}(k_{Sq}\bar{e}i\gamma_5 e\bar{q}q + k_{Pq}\bar{e}e\bar{q}i\gamma_5 q + k_{Tq}\bar{e}i\gamma_5\sigma_{\mu\lambda}e\bar{q}\sigma^{\mu\lambda}q), \tag{12}$$

where k_{Sq}, k_{Pq}, and k_{Tq} are real constants [24].

The constants of the interaction (1) are related to the e-q constants in Eq. (12) as

$$k_{Sa} = f_a^{(u)}k_{Su} + f_a^{(d)}k_{Sd}, \tag{13}$$

$$k_{Pa} = g_a^{(u)}k_{Pu} + g_a^{(d)}k_{Pd}, \tag{14}$$

$$k_{Ta} = h_a^{(u)}k_{Tu} + h_a^{(d)}k_{Td}, \tag{15}$$

where the quantities $f_a^{(q)} \equiv f_a^{(q)}(0)$, $g_a^{(q)} \equiv g_a^{(q)}(0)$, and $h_a^{(q)} \equiv h_a^{(q)}(0)$ are defined by

$$\langle a(p')|\bar{q}q|a(p)\rangle = f_a^{(q)}(q^2)\bar{u}_a u_a, \tag{16}$$

$$\langle a(p')|\bar{q}i\gamma_5 q|a(p)\rangle = g_a^{(q)}(q^2)\bar{u}_a i\gamma_5 u_a, \tag{17}$$

$$\langle a(p')|\bar{q}\sigma_{\mu\lambda}q|a(p)\rangle = h_a^{(q)}(q^2)\bar{u}_a\sigma_{\mu\lambda}u_a \tag{18}$$

$(a=p,n;\ q=u,d)$.

An estimate of the quantities $f_p^{(u)}$ and $f_p^{(d)}$ can be obtained from the σ term (deduced from pion-nucleon scattering data) and, assuming octet-type SU(3) breaking, from baryon mass splittings. These yield [25]

$$f_p^{(u)} \simeq 3.5, \tag{19}$$

$$f_p^{(d)} \simeq 2.8. \tag{20}$$

The neutron matrix elements are related to the proton matrix elements by charge symmetry:

$$f_n^{(u)} = f_p^{(d)}, \tag{21}$$

$$f_n^{(d)} = f_p^{(u)}. \tag{22}$$

The basis for estimates of the pseudoscalar matrix elements is the relation [26]

$$g_a^{(q)} = \frac{M_a}{m_q}\left[(\Delta q')_a + \frac{\alpha_s}{2\pi}(\Delta g)_a\right] \tag{23}$$

$(a=p,n;q=u,d,s)$, which follows from the divergence of the axial-vector current $\bar{q}\gamma_\mu\gamma_5 q$. In Eq. (23), M_a is the nucleon mass, $\Delta q'$ is the form factor at zero momentum transfer in the nucleon matrix element of the axial-vector current,

$$\langle a|\bar{q}\gamma_\lambda\gamma_5 q|a\rangle = (\Delta q')_a\bar{u}_a\gamma_\lambda\gamma_5 u_a, \tag{24}$$

and $(\Delta g)_a$ is defined by

$$\langle a|TrG_{\mu\nu}\tilde{G}_{\mu\nu}|a\rangle = -2M_a(\Delta g)_a\bar{u}_a i\gamma_5 u_a, \tag{25}$$

where $G_{\mu\nu}$ is the gluon field intensity and $\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\lambda\rho}G^{\lambda\rho}$.

For $(\alpha_s/2\pi)(\Delta g)_a$ we shall use the results obtained in Ref. [27]. In this reference $(\alpha_s/2\pi)(\Delta g)_a$ and $g_a^{(u)}+g_a^{(d)}+g_a^{(s)}$ were estimated using pseudoscalar meson pole dominance. The results depend on the η-nucleon and η'-nucleon coupling constants $g_{\eta NN}$ and $g_{\eta' NN}$. Since $g_{\eta NN}$ is not well known [28] and $g_{\eta' NN}$ is unknown [29], the author considers two cases: (a) setting $g_{\eta NN}=6.8$, as found in an analysis of the nucleon-nucleon potential, and (b) assuming $g_{\eta' NN}=g_{\eta NN}$. In both cases $(\Delta g)_a$ and $g_a^{(u)}+g_a^{(d)}+g_a^{(s)}$ are evaluated as functions of $g_{\eta' NN}$.

For the quantities $(\Delta q')_p$ we take $(\Delta u')_p=0.82\pm 0.03$, $(\Delta d')_p=-0.44\pm 0.03$, $(\Delta s')_p=-0.11\pm 0.03$ [30], deduced from data on polarized nucleon structure functions [31]. To obtain $(\Delta u')_n$, $(\Delta d')_n$, and $(\Delta s')_n$ we shall use charge symmetry and isospin invariance, respectively. The validity of isospin invariance for these quantities is consistent with the results of Ref. [27]. The experimental value $\Delta u'+\Delta d'+\Delta s'\simeq 0.27$ selects from the results of Ref. [27] $g_{\eta' NN}\simeq 1$ in case (a) and $g_{\eta' NN}\simeq 1.5$ in case (b) [32]. These imply $(\alpha_s/2\pi)(\Delta g)_p\simeq -0.42$, $(\alpha_s/2\pi)(\Delta g)_n\simeq -0.04$ in case (a) and $(\alpha_s/2\pi)(\Delta g)_p\simeq -0.27$, $(\alpha_s/2\pi)(\Delta g)_n\simeq 0.10$ in case (b) [33]. With these values and taking $m_u=5.1$ MeV, $m_d=9.3$ MeV [34], we obtain the following:

Case (a):

$$g_p^{(u)}\simeq 73.6, \tag{26}$$

$$g_p^{(d)}\simeq -86.8, \tag{27}$$

$$g_n^{(u)}\simeq -88.4, \tag{28}$$

$$g_n^{(d)}\simeq 78.8. \tag{29}$$

Case (b):

$$g_p^{(u)}\simeq 101.2, \tag{30}$$

$$g_p^{(d)}\simeq -71.6, \tag{31}$$

$$g_n^{(u)}\simeq -62.6, \tag{32}$$

$$g_n^{(d)}\simeq 92.9. \tag{33}$$

For the proton matrix elements of the tensor current we shall take

$$h_p^{(u)}\simeq 0.84, \tag{34}$$

$$h_p^{(d)}\simeq -0.23, \tag{35}$$

obtained in a lattice QCD calculation [35], and assume charge symmetry, which yields

$$h_n^{(u)}\simeq -0.23, \tag{36}$$

$$h_n^{(d)}\simeq 0.84. \tag{37}$$

Using in Eqs. (7)–(11) the values of the constants $f_a^{(q)}$, $g_a^{(q)}$, and $h_a^{(q)}$ given in Eqs. (19)–(22), (26)–(29) [corresponding to case (a)], and (34)–(37), the experimental results (2)–(6) imply the following bounds on the coupling constants of the CPV e-u and e-d interactions:

$$d(\mathrm{Tl}):\ |(k_{Su}+k_{Sd})-10^{-4}(2.7k_{Tu}-0.74k_{Td})|<4.5\times 10^{-8}, \tag{38}$$

$$d(\mathrm{Cs}):\ |(k_{Su}+k_{Sd})+1.3\times 10^{-3}(2.7k_{Tu}-0.74k_{Td})| < 7\times 10^{-6}, \tag{39}$$

$$d(\mathrm{Hg}):\ |(k_{Tu}-3.7k_{Td})+1.2(k_{Pu}-0.9k_{Pd})-0.4(k_{Su}+k_{Sd})| < 4.5\times 10^{-8}, \tag{40}$$

$$d(\mathrm{Xe}):\ |(k_{Tu}+21.5k_{Td})-4.5(k_{Pu}-0.8k_{Pd}) +1.2(k_{Su}+k_{Sd})|<5.5\times 10^{-5}, \tag{41}$$

$$\nu(\mathrm{TlF}):\ |(k_{Tu}+0.07k_{Td})+9\times 10^{-2}(k_{Pu}-1.4k_{Pd}) +0.14(k_{Su}+k_{Sd})|<8\times 10^{-7}. \tag{42}$$

The bounds for case (b) are obtained by the replacements

$$1.2(k_{Pu}-0.9k_{Pd})\rightarrow 0.84(k_{Pu}-1.5k_{Pd}), \tag{43}$$

$$-4.5(k_{Pu}-0.8k_{Pd})\rightarrow -2.1(k_{Pu}-2.3k_{Pd}), \tag{44}$$

$$9\times 10^{-2}(k_{Pu}-1.4k_{Pd})\rightarrow 0.16(k_{Pu}-0.5k_{Pd}), \tag{45}$$

in Eqs. (40)–(42).

III. *CP*-VIOLATING *e*-*u* AND *e*-*d* INTERACTIONS FROM LEPTOQUARK EXCHANGE

Leptoquarks are bosons which couple to lepton-quark pairs [16]. They appear in various extensions of the SM—for example, in grand unified theories [36], superstring-inspired models [37], supersymmetric models with *R*-parity violation [38], and composite models [39]. LQs which do not induce proton decay could be light enough to cause observable effects in some low-energy processes [40].

Assuming that the LQ-fermion couplings are dimensionless, the spin of the LQs can be only 0 or 1.

The lower bound on spin-1 LQ masses, independent of the LQ-fermion coupling constants, is 292 GeV for $LQ\rightarrow eq$ branching ratio $\beta\equiv \mathrm{BR}(LQ\rightarrow eq)=1$ and 282 GeV for $\beta=\frac{1}{2}$. These are obtained from experiments at the Tevatron, where LQs can be pair produced in $p\bar{p}$ scattering by the strong interaction. For spin-0 LQs the lower bounds are 242 GeV and 204 GeV for $\beta=1$ and $\beta=\frac{1}{2}$, respectively [41].

LQs coupled to the first fermion family can be produced also at the HERA collider. Experiments at HERA provide limits on the effective LQ-fermion coupling constants g'_{LQ} [for the definition see Eq. (50) or (51) below] for given LQ masses. The upper limits on the $g'_{LQ}s$, which are given up to $m_{LQ}\simeq 400$ GeV, are a few times 10^{-2} to a few times 10^{-1} for LQ masses 200 GeV$\lesssim m_{LQ}\lesssim$400 GeV [41].

For LQs with masses much larger than the c.m. energy available at the collider, limits on g'_{LQ}/m_{LQ} have been obtained from searches for contact interactions. The best of the upper limits, which are quoted only for chiral LQs (LQs that couple either to left-handed or to right-handed quarks), are of the order of $[10^{-3}G_F]^{1/2}$ [41].

The most general $\mathrm{SU}(2)_L\times \mathrm{U}(1)\times \mathrm{SU}(3)_c$ invariant, lepton-number-conserving (for Dirac neutrinos) and baryon-number-conserving Lagrangian for the couplings of spin-1 leptoquarks to a standard model family contains nine LQ states characterized by definite SM quantum numbers and a definite fermion number [42]. The couplings to the first family are given by

$$\begin{aligned}\mathcal{L}_{spin\text{-}1}=&[h_{1L}(\overline{u_L'}\gamma_\mu\nu_{eL}'+\overline{d_L'}\gamma_\mu e_L')+h_{1R}\overline{d_R'}\gamma_\mu e_R']U_1^\mu+\tilde{h}_{1R}\overline{u_R'}\gamma_\mu e_R'\tilde{U}_1^\mu+h_{3L}[(\overline{u_L'}\gamma_\mu\nu_{eL}'-\overline{d_L'}\gamma_\mu e_L')(U_3)_0^\mu\\&+\sqrt{2}\overline{u_L'}\gamma_\mu e_L'(U_3)_+^\mu+\sqrt{2}\overline{d_L'}\gamma_\mu\nu_{eL}'(U_3)_-^\mu]-(g_{2L}\overline{d_R^c}'\gamma_\mu e_L'+g_{2R}\overline{d_L^c}'\gamma_\mu e_R')(V_2)_+^\mu\\&+(g_{2L}\overline{d_R^c}'\gamma_\mu\nu_{eL}'+g_{2R}\overline{u_L^c}'\gamma_\mu e_R')(V_2)_-^\mu-\tilde{g}_{2L}\overline{u_R^c}'\gamma_\mu e_L'(\tilde{V}_2)_+^\mu+\tilde{g}_{2L}\overline{u_R^c}'\gamma_\mu\nu_{eL}'(\tilde{V}_2)_-^\mu+\text{H.c.}\end{aligned}\tag{46}$$

In Eq. (46) the primes on the fermion fields indicate that they are the weak eigenstates rather than mass eigenstates; $e_L=\frac{1}{2}(1-\gamma_5)$, $e_R=\frac{1}{2}(1+\gamma_5)$, etc. The first subscript on the LQ fields denotes the dimension of the multiplet, and the second represents the value of the third component of weak isospin $T_z(T_z=\pm\frac{1}{2}$, or 0, $\pm1)$. The fields with superscript c refer to the charge-conjugate fields: $u^c=C\overline{u}^T$, etc.

The analogous Lagrangian describing the couplings of spin-0 LQs, which also contains nine LQ states, is [43]

$$\begin{aligned}\mathcal{L}_{spin\text{-}0}=&[g_{1L}(\overline{u_L^c}'e_L'-\overline{d^c}'\nu_{eL}')+g_{1R}\overline{u_R^c}'e_R']S_1+\tilde{g}_{1R}\overline{d_R^c}'e_R'\tilde{S}_1-g_{3L}[(\overline{d_L^c}'\nu_{eL}'+\overline{u_L^c}'e_L')(S_3)_0+\sqrt{2}\overline{d_L^c}'e_L'(S_3)_+-\sqrt{2}\overline{u_L^c}'\nu_{eL}'(S_3)_-]\\&-(h_{2L}\overline{u_R'}e_L'+h_{2R}\overline{u_L'}e_R')(R_2)_++(h_{2L}\overline{u_R'}\nu_{eL}'-h_{2R}\overline{d_L'}e_R')(R_2)_--\tilde{h}_{2L}\overline{d_R'}e_L'(\tilde{R}_2)_++\tilde{h}_{2L}\overline{d_R'}\nu_{eL}'(\tilde{R}_2)_-+\text{H.c.}\end{aligned}\tag{47}$$

CP violation in the LQ-fermion couplings can originate from complex LQ-fermion coupling constants, fermion mixing, and LQ mixing [44].

As the CPV e-q interaction contains only scalar-, pseudoscalar-, and tensor-type couplings, it can receive contributions only from nonchiral LQs (LQs that couple to both left-handed and right-handed quarks). The e-q interaction is obtained by applying a Fierz transformation to the LQ-exchange four-fermion interaction. Spin-1 LQ exchange leads only to scalar- and pseudoscalar-type CPV interactions, while the CPV e-q interaction resulting from spin-0 LQ exchange contains also a tensor term [45].

A. Spin-1 leptoquarks

We shall consider first the case when the weak eigenstate LQs in Eq. (46) coincide with the mass eigenstates. A special case of this scenario is when only a single LQ multiplet is present. Inspection of Eq. (46) shows that the nonchiral LQs are the U_1, $(V_2)_+$, and $(V_2)_-$. Contributions to CPV e-q interactions arise only from U_1 and $(V_2)_+$.

U_1. The e-q interaction from U_1 exchange is given by

$$H=\frac{h_{1L}h_{1R}^*}{4M_1^2}(\overline{e_R'}\gamma_\mu d_R'\overline{d_L'}\gamma_\mu e_L')+\text{H.c.},\tag{48}$$

where M_1 is the mass of the U_1. Rewriting the Hamiltonian (48) in terms of the electron and quark mass eigenstates, we obtain

$$H=\frac{h_{1L}'h_{1R}'^*}{4M_1^2}(\overline{e}_R\gamma_\mu d_R\overline{d}_L\gamma_\mu e_L)+\text{H.c.},\tag{49}$$

where the effective LQ-fermion coupling constants h_{1L}' and h_{1R}' are given by

$$h_{1L}'=h_{1L}(V_L^{(e)})_{ee}(V_L^{(d)})_{dd}^*,\tag{50}$$

$$h_{1R}'=h_{1R}(V_R^{(e)})_{ee}^*(V_R^{(d)})_{dd}.\tag{51}$$

In Eqs. (50) and (51), $V_L^{(e)}$, $V_R^{(e)}$, $V_L^{(d)}$, and $V_R^{(d)}$ are the mixing matrices of the left-handed and right-handed charged leptons and of the left-handed and right-handed charge $-\frac{1}{3}$ quarks, respectively. In the following, the primed LQ-fermion coupling constants will always denote the effective coupling constants, which include the appropriate fermion mixing matrix elements.

The interaction (49) has a *CP*-invariant component and, for complex $h_{1L}'h_{1R}'^*$, it contributes also to the CPV interaction (12). If the spin-1 LQs are elementary, they are gauge bosons and, since the gauge interactions are *CP* invariant, the coupling constants h_{1L} and h_{1R} are real. However, the product $h_{1L}'h_{1R}'^*$ can still be complex, due to the complex phases that are present in general in the elements of the mixing matrices. Note that such phases cannot be removed by redefining the phases of the electron and quark fields, since the operator in Eq. (49) is invariant under $e\to e^{i\Phi_e}e$ and under $d\to e^{i\Phi_d}d$. Applying a Fierz transformation to the Hamiltonian (49), we obtain, for the CPV component $H^{(-)}$ of Eq. (49),

$$H^{(-)}=\frac{\text{Im}(h_{1L}'h_{1R}'^*)}{M_1^2}(\overline{e}i\gamma_5e\overline{d}d-\overline{e}e\overline{d}i\gamma_5d).\tag{52}$$

Thus U_1 generates a CPV e-q interaction of the form (12) with

$$k_{Sd}=-k_{Pd}=\left(\frac{\mathrm{Im}(h'_{1L}h'^{*}_{1R})}{M_1^2}\right)\frac{\sqrt{2}}{G_F},$$

$$k_{Su}=k_{Pu}=k_{Tu}=k_{Td}=0. \tag{53}$$

Inspection shows that the best limit on k_{Sd} comes from $d(\mathrm{Tl})$. Equation (38) reduces in this case to

$$|k_{Sd}|<4.5\times10^{-8}, \tag{54}$$

so that we obtain

$$|\mathrm{Im}(h'_{1L}h'^{*}_{1R})|<2\times10^{-8}\left(\frac{M_1}{250\ \mathrm{GeV}}\right)^2. \tag{55}$$

We normalized the bound in Eq. (55) with respect to 250 GeV, which is close to the experimental lower limit on the mass of LQs.

$(V_2)_+$. In the same way, we obtain for the contribution of $(V_2)_+$ an e-q interaction characterized by

$$k_{Sd}=-k_{Pd}=\left(\frac{\mathrm{Im}(g'_{2L}g'^{*}_{2R})}{M_2^2}\right)\frac{\sqrt{2}}{G_F},$$

$$k_{Su}=k_{Pu}=k_{Tu}=k_{Td}=0. \tag{56}$$

Thus, as for the U_1, we have

$$|\mathrm{Im}(g'_{2L}g'^{*}_{2R})|<2\times10^{-8}\left(\frac{M_2}{250\ \mathrm{GeV}}\right)^2. \tag{57}$$

If more than one LQ multiplet is present, LQs of the same electric charge (Q) will generally mix [46]. We find that the mixing induces further contributions to CPV e-q interactions. Inspections shows that such contributions can arise from the mixing of the $Q=\frac{2}{3}$ pair U_1, $(U_3)_0$, the $Q=\frac{5}{3}$ pair $\tilde{U}_1$, $(U_3)_+$, and the $Q=\frac{1}{3}$ pair $(V_2)_-$, $(\tilde{V}_2)_+$.

U_1, $(U_3)_0$. We shall write

$$U_1=U_a\cos\beta_1+U_b\sin\beta_1,$$

$$(U_3)_0=(-U_a\sin\beta_1+U_b\cos\beta_1)e^{i\varphi_1}, \tag{58}$$

where U_a and U_b are the mass eigenstates. Note that the phase $e^{i\varphi_1}$ cannot be removed by redefining the phases of the mass eigenstates U_a and U_b, and is therefore a further source of *CP* violation. The e-q interaction due to mixing is given by

$$H_{mixing}=\frac{1}{4}\left(\frac{1}{M_a^2}-\frac{1}{M_b^2}\right)\sin\beta_1\cos\beta_1 e^{i\varphi_1}h'_{3L}h'^{*}_{1R}\bar{d}\gamma_\mu \times(1-\gamma_5)e\bar{e}(1+\gamma_5)d. \tag{59}$$

The total CPV e-q interaction from the $U_1-(U_3)_0$ system has therefore

$$k_{Sd}=-k_{Pd}=\left[\left(\frac{1}{M_a^2}\cos^2\beta_1+\frac{1}{M_b^2}\sin^2\beta_1\right)\mathrm{Im}(h'_{1L}h'^{*}_{1R}) +\left(\frac{1}{M_a^2}-\frac{1}{M_b^2}\right)\sin\beta_1\cos\beta_1\mathrm{Im}(e^{i\varphi_1}h'_{3L}h'^{*}_{1R})\right]\frac{\sqrt{2}}{G_F},$$

$$k_{Su}=k_{Pu}=k_{Tu}=k_{Td}=0, \tag{60}$$

where the first term is the U_1 contribution modified by the mixing and the second term comes from mixing. The bound on the LQ-fermion effective coupling constants, obtained from $d(\mathrm{Tl})$, is

$$\left|\mathrm{Im}(h'_{1L}h'^{*}_{1R})+\left(\frac{1}{M_a^2}-\frac{1}{M_b^2}\right)\left(\frac{1}{M_a^2}\cos^2\beta_1 +\frac{1}{M_b^2}\sin^2\beta_1\right)^{-1}\sin\beta_1\cos\beta_1\mathrm{Im}(e^{i\varphi_1}h'_{3L}h'^{*}_{1R})\right| <2\times10^{-8}\left[\left(\frac{1}{250\ \mathrm{GeV}}\right)^2 \times\left(\frac{1}{M_a^2}\cos^2\beta_1+\frac{1}{M_b^2}\sin^2\beta_1\right)^{-1}\right]. \tag{61}$$

$\tilde{U}_1$, $(U_3)_+$. The CPV e-q interaction, which arises in this case only through LQ mixing, has

$$k_{Su}=-k_{Pu} =\sqrt{2}\left(\frac{1}{\tilde{M}_a^2}-\frac{1}{\tilde{M}_b^2}\right)\sin\tilde{\beta}_1\cos\tilde{\beta}_1\mathrm{Im}(e^{i\tilde{\varphi}_1}\tilde{h}'_{1R}h'^{*}_{3L})\frac{\sqrt{2}}{G_F},$$

$$k_{Sd}=k_{Pd}=k_{Td}=k_{Tu}=0. \tag{62}$$

In Eq. (62), $\tilde{\beta}_1$ and $\tilde{\varphi}_1$ are the $\tilde{U}_1$-$(U_3)_+$ mixing angle and *CP*-violating phase, respectively, defined in the same way as β_1 and φ_1 in Eq. (58). The limit on k_{Su} from $d(\mathrm{Tl})$ is $|k_{Su}|<4.5\times10^{-8}$. A slightly better limit comes from $d(\mathrm{Hg})$. Using the relations in Eq. (62), the limit from $d(\mathrm{Hg})$ [Eq. (40)] becomes $|k_{Su}|<3\times10^{-8}$ for case (a) and $|k_{Su}|<3.5\times10^{-8}$ for case (b). However, the limits from $d(\mathrm{Hg})$ cannot be regarded as safe. The reason is that in $d(\mathrm{Hg})$ the contributions from the pseudoscalar- and scalar-type interactions are of the same order of magnitude and therefore, in view of the uncertainties in the values of the nucleon matrix elements, which for $g_a^{(q)}$ could be large, the possibility of significant cancellations cannot be ruled out. We shall use therefore the limit from $d(\mathrm{Tl})$, obtaining

$$|\mathrm{Im}(e^{i\tilde{\varphi}_1}\tilde{h}'_{1R}h'^{*}_{3L})|<1.5\times10^{-8}\left[\left(\frac{1}{250\ \mathrm{GeV}}\right)^2\frac{1}{\sin\tilde{\beta}_1\cos\tilde{\beta}_1} \times\left(\frac{1}{\tilde{M}_a^2}-\frac{1}{\tilde{M}_b^2}\right)^{-1}\right]. \tag{63}$$

$(V_2)_-$, $(\tilde{V}_2)_+$. The CPV e-q interaction from the V_2 and $\tilde{V}_2$ LQs consists of the e-d interaction from $(V_2)_+$ exchange, and an e-u interaction generated by $(V_2)_-$-$(\tilde{V})_+$ mixing. The total contribution is a CPV e-q interaction with

$$k_{Sd}=-k_{Pd}=\frac{\mathrm{Im}(g'_{2L}g'^{*}_{2R})}{M_2^2}\frac{\sqrt{2}}{G_F},$$
$$k_{Su}=-k_{Pu}=-\left[\left(\frac{1}{M_{2a}^2}-\frac{1}{M_{2b}^2}\right)\sin\beta_2\cos\beta_2\mathrm{Im}(e^{i\varphi_2}g'_{2R}\tilde{g}'^{*}_{2L})\right]\frac{\sqrt{2}}{G_F},$$
$$k_{Tu}=k_{Td}=0. \tag{64}$$

The limit from $d(\mathrm{Tl})$ in this case is

$$|k_{Su}+k_{Sd}|<4.5\times10^{-8}. \tag{65}$$

Thus we need a further limit to constrain both k_{Su} and k_{Sd}. The second most stringent bound is

$$|k_{Su}-0.4k_{Sd}|<3\times10^{-8}\quad[\text{case (a)}] \tag{66}$$
$$|k_{Su}-0.7k_{Sd}|<3.5\times10^{-8}\quad[\text{case (b)}], \tag{67}$$

obtained from $d(\mathrm{Hg})$ using the relations in Eq. (64). Equation (65), combined with Eq. (66) (which gives the weaker bound), yields

$$|k_{Su}|<3.5\times10^{-8}, \tag{68}$$
$$|k_{Sd}|<5.5\times10^{-8}, \tag{69}$$

so that we obtain

$$|\mathrm{Im}(g'_{2L}g'^{*}_{2R})|\lesssim1.5\times10^{-8}\left(\frac{M_2}{250\ \mathrm{GeV}}\right)^2, \tag{70}$$

$$|\mathrm{Im}(e^{i\varphi_2}g'_{2R}\tilde{g}'^{*}_{2L})|\lesssim2.5\times10^{-8}\left[\left(\frac{1}{250\ \mathrm{GeV}}\right)^2\frac{1}{\sin\beta_2\cos\beta_2}\times\left(\frac{1}{M_{2a}^2}-\frac{1}{M_{2b}^2}\right)^{-1}\right]. \tag{71}$$

However, it should be noted that the bounds (66) and (67), and therefore the bounds (68)–(71) are unreliable, as noted earlier. We present them here only as illustrations of what constraints one obtains if all inputs are taken at face value. Bounds from $d(\mathrm{Xe})$ and $\nu(\mathrm{TlF})$, which are weaker, suffer from the same problem as the ones from $d(\mathrm{Hg})$.

B. Spin-0 leptoquarks

In the absence of LQ mixing only S_1 and $(R_2)_+$ contribute to CPV e-q interactions. The CPV e-q interaction from $(R_2)_+$ has been considered in Ref. [9] and from S_1 in Refs. [9] and [12]. We include them here for completeness and to update the discussion and the bounds on the effective leptoquark-fermion coupling constants.

S_1. The contribution from S_1 exchange is given by

$$H^{(-)}=\frac{1}{4m_1^2}\mathrm{Im}(g'_{1L}g'^{*}_{1R})\left(\bar{e}e\bar{u}i\gamma_5u+\bar{e}i\gamma_5e\bar{u}u+\frac{1}{2}\bar{e}i\gamma_5\sigma_{\lambda\mu}e\bar{u}\sigma^{\lambda\mu}u\right). \tag{72}$$

As mentioned earlier, a new feature of spin-0 LQs is the presence of a tensor term in the CPV e-q interaction. Comparing Eq. (72) with the interaction (12), we have

$$k_{Su}=k_{Pu}=2k_{Tu}=\frac{1}{4m_1^2}\mathrm{Im}(g'_{1L}g'^{*}_{1R}),$$
$$k_{Sd}=k_{Pd}=k_{Td}=0. \tag{73}$$

The limit from $d(\mathrm{Tl})$, which is the most stringent, becomes

$$|k_{Su}|<4.5\times10^{-8}, \tag{74}$$

where we used $k_{Su}-2.7\times10^{-4}k_{Tu}=k_{Su}-2.7\times10^{-4}\times(\frac{1}{2}k_{Su})\simeq k_{Su}$. In terms of the LQ coupling constants the bound (74) reads

$$|\mathrm{Im}(g'_{1L}g'^{*}_{1R})|<8\times10^{-8}\left(\frac{m_1}{250\ \mathrm{GeV}}\right)^2. \tag{75}$$

$(R_2)_+$. The $(R_2)_+$-exchange CPV e-q interaction is given by the Hamiltonian (12) with

$$k_{Su}=k_{Pu}=-2k_{Tu}=-\frac{1}{4m_2^2}\mathrm{Im}(h'_{2L}h'^{*}_{2R}). \tag{76}$$

The most stringent limit comes again from $d(\mathrm{Tl})$. We obtain

$$|\mathrm{Im}(h'_{2L}h'^{*}_{2R})|<8\times10^{-8}\left(\frac{m_2}{250\ \mathrm{GeV}}\right)^2. \tag{77}$$

Inspection shows that contributions arising from LQ mixing come from the $Q=\frac{1}{3}$ pair S_1, $(S_3)_0$, the $Q=\frac{4}{3}$ pair $\tilde{S}_1$, $(S_3)_+$, and the $Q=\frac{2}{3}$ pair $(R_2)_-$, $(\tilde{R}_2)_+$.

S_1, $(S_3)_0$. The CPV e-q interaction from the S_1-$(S_3)_0$ system consists of the direct term from S_1 and a further e-u interaction due to S_1-$(S_3)_0$ mixing. The complete interaction is characterized by

$$k_{Su}=k_{Pu}=2k_{Tu}=\frac{1}{4}\left(\frac{1}{m_a^2}\cos^2\alpha_1+\frac{1}{m_a^2}\sin^2\alpha_2\right)\mathrm{Im}(g'_{1L}g'^{*}_{1R})-\frac{1}{4}\left(\frac{1}{m_a^2}-\frac{1}{m_b^2}\right)\sin\alpha_1\cos\alpha_1\mathrm{Im}(e^{i\psi_1}g'_{3L}g'^{*}_{1R}) \tag{78}$$

where we have defined the mixing angle α_1 and the CPV phase ψ_1 in the same way as for the spin-1 LQs:

$$S_1 = S_a \cos\alpha_1 + S_b \sin\alpha_1,$$

$$(S_3)_0 = (-S_a \sin\alpha_1 + S_b \cos\alpha_1) e^{i\psi_1}. \tag{79}$$

The bound on the LQ coupling constants from $d(\mathrm{Tl})$ is

$$\left| \mathrm{Im}(g'_{1L} g'^{*}_{1R}) + \left(\frac{1}{m_a^2} - \frac{1}{m_b^2}\right)\left(\frac{1}{m_a^2}\cos^2\alpha_1 + \frac{1}{m_b^2}\sin^2\alpha_1\right)^{-1} \times \sin\alpha_1 \cos\alpha_1 \mathrm{Im}(e^{i\psi_1} g'_{3L} g'^{*}_{1R}) \right| < 8\times 10^{-8}\left[\left(\frac{1}{250\ \mathrm{GeV}}\right)^2 \left(\frac{1}{m_a^2}\cos^2\alpha_1 + \frac{1}{m_b^2}\sin^2\alpha_1\right)^{-1}\right]. \tag{80}$$

$\tilde{S}_1$, $(S_3)_+$. The mixing contribution, which is in this case the only one, has

$$k_{Sd} = k_{Pd} = 2k_{Td} = -\frac{\sqrt{2}}{4}\left(\frac{1}{\tilde{m}_a^2} - \frac{1}{\tilde{m}_b^2}\right)\sin\tilde{\alpha}_1 \cos\tilde{\alpha}_1 \mathrm{Im}(e^{i\tilde{\psi}_1} g'_{3L} g'^{*}_{1R}),$$

$$k_{Su} = k_{Pu} = k_{Tu} = 0. \tag{81}$$

The limit on k_{Sd} from $d(\mathrm{Tl})$ is $|k_{Sd} - 2.7\times 10^{-4} k_{Td}| \simeq |k_{Sd}| < 4.5\times 10^{-8}$. From $d(\mathrm{Hg})$ we find $|k_{Sd}| < 1.5\times 10^{-8}$, but for spin-0 LQs one has to worry about a potential cancellation in $d(\mathrm{Hg})$ [and in $d(\mathrm{Xe})$, $\nu(\mathrm{TlF})$] even more than for spin-1 LQs, because of the tensor contribution, which is related to the scalar and pseudoscalar contributions. Using the limit from $d(\mathrm{Tl})$, we obtain

$$|\mathrm{Im}(e^{i\tilde{\psi}_1} g'_{3L} g'^{*}_{1R})| < 6\times 10^{-8}\left[\left(\frac{1}{250\ \mathrm{GeV}}\right)^2 \frac{1}{\sin\tilde{\alpha}_1 \cos\tilde{\alpha}_1}\left(\frac{1}{\tilde{m}_a^2} - \frac{1}{\tilde{m}_b^2}\right)^{-1}\right]. \tag{82}$$

$(R_2)_-$, $(\tilde{R}_2)_+$. The CPV e-q interaction from the $(R_2)_-$-$(\tilde{R}_2)_+$ system is a sum of the direct contribution from $(R_2)_+$ and of an e-d interaction due to $(R_2)_-$-$(\tilde{R}_2)_+$ mixing. The total interaction has

$$k_{Su} = k_{Pu} = -2k_{Tu} = -\frac{1}{4}\left(\frac{1}{m_{2a}^2}\cos^2\alpha_2 + \frac{1}{m_{2b}^2}\sin^2\alpha_2\right)\mathrm{Im}(h'_{2L} h'^{*}_{2R}), \tag{83}$$

$$k_{Sd} = k_{Pd} = -2k_{Td} = \frac{1}{4}\left(\frac{1}{m_{2a}^2} - \frac{1}{m_{2b}^2}\right)\sin\alpha_2 \cos\alpha_2 \mathrm{Im}(e^{i\psi_2} h'_{2L} h'^{*}_{2R}). \tag{84}$$

Combining the bound $|k_{Su} + k_{Sd}| < 4.5\times 10^{-8}$ from $d(\mathrm{Tl})$ with the bound

$$|k_{Su} + 1.2k_{Sd}| < 1.5\times 10^{-7} \quad [\text{case (a)}], \tag{85}$$

$$|k_{Su} - 3.2k_{Sd}| < 7.5\times 10^{-7} \quad [\text{case (b)}], \tag{86}$$

from $d(\mathrm{Hg})$, we find

$$|k_{Su}| < 10^{-6} \tag{87}$$

and

$$|k_{Sd}| < 10^{-6}, \tag{88}$$

so that

$$|\mathrm{Im}(h'_{2L} h'^{*}_{2R})| < 2\times 10^{-6}\left(\frac{m_2}{250\ \mathrm{GeV}}\right)^2, \tag{89}$$

$$|\mathrm{Im}(e^{i\psi_2} h'_{2L} h'^{*}_{2R})| < 2\times 10^{-6}\left[\left(\frac{1}{250\ \mathrm{GeV}}\right)^2 \frac{1}{\sin\alpha_2 \cos\alpha_2} \times \left(\frac{1}{m_{2a}^2} - \frac{1}{m_{2b}^2}\right)^{-1}\right]. \tag{90}$$

As emphasized earlier, the bounds from $d(\mathrm{Hg})$, and therefore Eqs. (87)–(90), cannot be regarded as safe.

C. Other contributions of the CPV LQ-fermion couplings

The same couplings which induce the CPV e-q interactions contribute at the one-loop level to the electron EDM (d_e) [9,11] and to the color EDM of the quarks d_q^c. Both give additional contributions to atomic EDMs and to molecular CPV observables. These contributions are, however, much smaller than the contributions from the e-q interactions.

Let us consider the contribution of d_e induced by the S_1 to $d(\mathrm{Tl})$. The one-loop diagrams, involving the LQ and quark in the loop, yield [47]

$$d_e(S_1) \simeq -\frac{7}{96 m_1^2} m_u \mathrm{Im}(g'_{1L} g'^{*}_{1R})\left(1 + \frac{4}{7}\ln\frac{m_u^2}{m_1^2}\right) \simeq -\frac{7}{24\sqrt{2}\pi^2} G_F m_u k_{Su}\left(1 + \frac{4}{7}\ln\frac{m_u^2}{m_1^2}\right) \simeq -(2.5\times 10^{-23}\ e\ \mathrm{cm}) k_{Su}\left(1 + \frac{4}{7}\ln\frac{m_u^2}{m_1^2}\right), \tag{91}$$

where we used Eq. (73). The contribution of d_e to $d(\mathrm{Tl})$ is $d(\mathrm{Tl})_{d_e} \simeq -585 d_e$ [7], so that $d(\mathrm{Tl})$ with both the e-q and d_e contributions included is [see Eq. (7)]

$$d(\mathrm{Tl}) \simeq \left[2.1\times 10^{-17} - 1.4\times 10^{-20} \left(1 + \frac{4}{7} \ln \frac{m_u^2}{m_1^2} \right) \right] k_{Su} \;\; e\ \mathrm{cm}. \quad (92)$$

Thus the contribution from d_e is smaller by two orders of magnitude than the one from the e-q interaction even for $m_1 \simeq 10^4$ TeV.

The quark color EDM d_u^c induced by the S_1 through one-loop diagrams is given by [47]

$$d_u^c \simeq -\eta_{cdm} \frac{m_e k_{Su} G_F}{24\sqrt{2}\pi^2} \simeq 3.5\times 10^{-25} k_{Su} \;\; \mathrm{cm}, \quad (93)$$

where η_{cdm} is a renormalization group factor, estimated to be of the order of unity [48], which accounts for the QCD evolution of d_q^c from the scale $\sim m_{LQ}$ to ~ 1 GeV, and k_{Su} is given in Eq. (73).

The quark color EDMs contribute to atomic EDMs and to ν through the Schiff moments Q_S of the nuclei [7]. The contribution of Q_S to $d(\mathrm{Tl})$ is given by [49]

$$d(\mathrm{Tl})_{Q_S} = -1.6\times 10^{-17} \left(\frac{Q_S(\mathrm{Tl})}{e\ \mathrm{fm}^3} \right) e\ \mathrm{cm}. \quad (94)$$

The Schiff moment of ^{205}Tl was calculated in Ref. [50], obtaining

$$Q_S(\mathrm{Tl}) = (1.2\eta_{pp} - 1.4\eta_{pn}) \times 10^{-8} \;\; e\ \mathrm{fm}^3, \quad (95)$$

where η_{pp} and η_{pn} are parameters in a general P,T-violating nucleon-nucleon interaction. The parameters η_{pp} and η_{pn} are dominated by contributions from pion exchange [51]. Expressing them in terms of the P,T-violating pion-nucleon coupling constants $\overline{g}_{\pi NN}^{(I)\prime}$ (I=isospin) [52], we obtain

$$d(\mathrm{Tl})_{Q_S} \simeq 1.4\times 10^{-17} (2.6 \overline{g}_{\pi NN}^{(0)\prime} - 0.2 \overline{g}_{\pi NN}^{(1)\prime} + 5.2 \overline{g}_{\pi NN}^{(2)\prime}) e\ \mathrm{cm}. \quad (96)$$

The quark color EDMs do not contribute to $\overline{g}_{\pi NN}^{(2)\prime}$. Their contribution to $\overline{g}_{\pi NN}^{(0)\prime}$ and $\overline{g}_{\pi NN}^{(1)\prime}$ has been estimated in Ref. [53], obtaining

$$\overline{g}_{\pi NN}^{(0)\prime} \simeq 10^{14} \kappa_0 (d_u^c + d_d^c) \;\; \mathrm{cm}^{-1}, \quad (97)$$

$$\overline{g}_{\pi NN}^{(1)\prime} \simeq 10^{14} \kappa_1 (d_u^c - d_d^c) \;\; \mathrm{cm}^{-1}, \quad (98)$$

with κ_0 in the range (-0.5)–1.5 and κ_1 in the range 1–6. Using these values, together with $d_d^c = 0$ and d_u^c from Eq. (93), we find

$$|d(\mathrm{Tl})_{Q_S}| \simeq 1.4\times 10^{-3} |(2.6\kappa_0 - 0.2\kappa_1) d_u^c| \lesssim 3\times 10^{-27} k_{Su} \;\; e\ \mathrm{cm}, \quad (99)$$

which is negligible even relative to $d(\mathrm{Tl})_{d_e}$.

Inspection shows that, barring fine-tuned cancellations among k_{S_q}, k_{P_q}, and k_{T_q} and also between k_{Su} and k_{Sd} for the contributions from the V_2-$\widetilde{V}_2$ and R_2-$\widetilde{R}_2$ LQs, the dominance of the contributions from the e-q interactions holds for all LQ contributions in all the atomic EDMs we considered and in the molecular parameter $\nu(\mathrm{TlF})$.

The CPV LQ-fermion couplings contribute also to the EDM of the neutron, d_n. The neutron EDM was estimated in terms of the quark color and electric dipole moments in Ref. [54], with the result

$$d_n \simeq (1 \pm 0.5)[0.55 e (d_d^c + 0.5 d_u^c) + 0.7 (d_d - 0.25 d_u)]. \quad (100)$$

For the contribution of the S_1 one has $d_d^c = 0$, d_u^c is given in Eq. (93), and the quark EDMs d_q are $d_d = 0$ and

$$d_u \simeq \eta_{edm} \frac{m_e G_F k_{Su}}{3\sqrt{2}\pi^2} \left(1 + \frac{3}{4} \ln \frac{m_u^2}{m_1^2} \right), \quad (101)$$

where k_{Su} is given in Eq. (73) and $\eta_{edm} \simeq 1.53$ is the renormalization group evolution factor [55]. From Eqs. (93), (100), amd (101) we find

$$d_n \simeq 0.5(1 \pm 0.55) \times 10^{-24} k_{Su} \left(1 + \frac{3}{4} \ln \frac{m_u^2}{m_1^2} \right) e\ \mathrm{cm}. \quad (102)$$

The experimental limit $|d_n| < 6.3\times 10^{-26}$ e cm (90% C.L.) [56] implies, for $m_1 \lesssim 10^4$ TeV, $|k_{Su}| \lesssim 10^{-2}$, which is five orders of magnitude weaker than the limit (74) from the CPV e-N interaction. The limits from d_n for the other LQ contributions are similarly weak.

Fermion mixing creates from first-family LQ couplings also flavor-changing neutral-current interactions. In particular, for couplings involving d_L' and d_R' there can be contributions to the CPV parameters ϵ and ϵ'/ϵ in $K_L \to 2\pi$ decays [57]. Inspections shows that, based on the calculations in Ref. [57], the limits on k_{Su} and k_{Sd} from these are not better than $10^{-6}\ |(V_{L,R}^{(d)})_{dd}/(V_{L,R}^{(d)})_{ds}|^k$, where $k=2$ and 1 for ϵ and ϵ'/ϵ, respectively. These limits are in general complementary to the limits from the CPV e-q interactions because of the new mixing matrix elements involved, which can even bring in different *CP*-violating phases.

Quark mixing gives rise also to e-s (and e-c, etc.) interactions. The strength of these relative to the strength of the e-d interactions involves the factor $|(V_{L,R}^{(d)})_{ds}/(V_{L,R}^{(d)})_{dd}|^2$, which is expected to be small.

IV. CONCLUSIONS

The purpose of this investigation was to deduce the information on the *CP*-violating couplings of spin-1 and spin-0 leptoquarks to the first fermion family from experimental bounds on the *CP*-violating electron-nucleon interactions. We considered both contributions from single leptoquarks, assumed to be in mass eigenstates, and contributions arising as a result of mixing of leptoquarks of given standard model quantum numbers. Since the pseudoscalar and (for spin-0 leptoquarks) tensor electron-quark coupling constants are related to the scalar ones, all contributions depend only on two independent coupling constants—for example, k_{Su} and k_{Sd}. When only one of these is present, which is the situation in most cases, the best upper limit on the *CP*-violating products of the effective leptoquark-fermion coupling constants comes from the experimental bound on the electric dipole moment of the ^{205}Tl atom. These limits are in the range $\sim 10^{-7}$ to $\sim 10^{-8}$ for $m_{LQ}=250$ GeV and maximal LQ mixing [see Eqs. (55), (57), (61), (63), (75), (77), (80), and (82)]. The V_2-$\tilde{V}_2$ and R_2-$\tilde{R}_2$ systems contribute to both k_{Su} and k_{Sd}. To limit both, a second constraint is needed. The most stringent for this is the experimental bound on the ^{199}Hg electric dipole moment $d(\mathrm{Hg})$. However, the implied limits on k_{Su} and k_{Sd} [Eqs. (68), (69), (87), (88), and therefore (70), (71), (89), and (90)] are not safe, since cancellations among the various contributions in $d(\mathrm{Hg})$ cannot be ruled out. The same is true about the limits from the remaining atomic electric dipole moments and from the nuclear spin-flip parameter of the TlF molecule.

The leptoquark-fermion couplings which give rise to the *CP*-violating e-u and e-d interactions give contributions also to the electron electric dipole moment, quark color EDMs, and the electric dipole moment of the neutron. Barring some fine-tuned cancellations, the best limits on the *CP*-violating products of the effective leptoquark-fermion coupling constants come from the experimental limits on the electron-nucleon interactions.

We note yet that limits from atomic electric dipole moments and molecular *CP*-violating observables are expected to improve in the future considerably [58].

ACKNOWLEDGMENTS

I would like to thank S. D. Bass, T. P. Cheng, T. E. Chupp, T. Hatsuda, M. Karliner, M. Pospelov, and M. V. Romalis for useful correspondence. This work was supported by the Department of Energy under contract W-7405-ENG-36.

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