New constraints on axion-mediated P,T-violating interaction from electric dipole moments of diamagnetic atoms

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The exchange of an axion-like particle between atomic electrons and the nucleus may induce electric dipole moments (EDMs) of atoms and molecules. This interaction is described by a parity-and time-reversal-invariance-violating potential which depends on the product of a scalar $g^s$ and a pseudoscalar $g^p$ coupling constant. We consider the interaction with the specific combination of these constants, $g_s^x g_N^p$, which gives significant contributions to the EDMs of diamagnetic atoms. In this paper, we calculate these contributions to the EDMs of $^{199}$Hg, $^{129}$Xe, $^{211}$Rn and $^{225}$Ra for a wide range of axion masses. Comparing these results with recent experimental EDM measurements, we place new constraints on $g_s^x g_N^p$. The most stringent atomic EDM limits come from $^{199}$Hg and improve on existing laboratory limits from other experiments for axion masses exceeding $10^{-2}$ eV.

I. INTRODUCTION

In field theory, the interaction of the axion field $a$ with fermions $\psi$ may be described by the Lagrangian density

$$\mathcal{L}_{\text{int}} = a \sum_x \bar{\psi} (g_s^x + i g_p^x \gamma_5) \psi, \quad (1)$$

where $g_s^x$ and $g_p^x$ are model-dependent coupling constants and $\gamma_5 = -i \gamma_0 \gamma_1 \gamma_2 \gamma_3$ in the notation of [1] for Dirac matrices. This Lagrangian appears naturally in the case of the canonical axion, which solves the strong CP problem of quantum chromodynamics [2–8]. In Eq. (1), we assume, however, a generic axion-like particle, which couples to different fermions with independent constants $g_s^x$ and $g_p^x$. Consistency with various experimental data imposes severe constraints on different combinations of such couplings, see, e.g., Ref. [9] for a review. Since these interactions are extremely weak, the axion can naturally be considered a candidate for dark matter [10,12].

In atomic phenomena, the interaction [11] implies the exchange of an axion between the atomic electrons and the nucleus that can induce P,T-violating phenomena. Recently, Ref. [13] considered the case when the pseudoscalar interaction constant $g_p$ corresponds to the electron, while the scalar interaction constant $g^s$ corresponds to either another electron or a nucleon. This provided a significant improvement over previous limits on these interaction constants. In this paper, we consider the opposite case, namely when the constant $g^s$ corresponds to the interaction of the axion with an electron, while $g^p$ corresponds to the interaction with a nucleon. The P,T-violating potential due to the exchange of an axion of mass $m_a$ with a nucleon of mass $m_N$ reads [13,14]

$$V(r) = -\frac{g_s^x g_N^p}{8 \pi m_N} \sigma_N \cdot \nabla \left( e^{-m_a r}/r \right) \gamma^0, \quad (2)$$

where $\sigma_N$ is the nucleon spin unit vector and the Dirac matrix $\gamma^0$ corresponds to the atomic electrons. This potential induces EDMs in atoms with non-vanishing nuclear spin and gives the dominant contribution in atoms with a closed electron shell in the ground state (so-called diamagnetic atoms). We perform numerical calculations of the corresponding EDMs for atomic $^{199}$Hg, $^{129}$Xe, $^{211}$Rn and $^{225}$Ra to interpret existing experimental data. We find that the most stringent constraint arises from the recent EDM measurement in $^{199}$Hg [15]:

$$d(^{199}\text{Hg}) = (2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \times 10^{-30} \text{e cm}. \quad (3)$$

This allows us to place new bounds on the combination of coupling constants $g_s^x g_N^p$ for a wide range of axion masses. Measurements of EDMs in the other diamagnetic atoms give less stringent constraints. We note that in the limit of a large axion mass, the potential (2) reduces to the following contact interaction

$$\lim_{m_a \to \infty} m_a^2 V(r) = -\frac{g_s^x g_N^p}{2 m_N} \sigma_N \cdot \nabla [s^3(r)] \gamma^0. \quad (4)$$

In field theory, this potential corresponds to the parity-and time-reversal-invariance-violating four-fermion interaction Lagrangian density

$$\mathcal{L} = -\frac{G_F}{\sqrt{2}} C_{PS} \bar{N} i \gamma_5 N \bar{e} e, \quad (5)$$

where $N$ and $e$ denote the nucleon and electron fields, respectively; $G_F$ is the Fermi constant and $C_{PS} = -\sqrt{2} g_s^x g_N^p/(G_F m_N^2)$. The contributions to the EDMs of diamagnetic atoms due to this operator were studied in previous works [16,17]. In the next section, we extend these earlier calculations to the potential (2), which is defined for an arbitrary axion mass.

II. CALCULATIONS AND RESULTS

The potential (2) describes the interaction of a non-polarized electron with a polarized nucleon with spin $\sigma_N$. To apply this potential to the electron-nucleus interaction in an atom, we have to average it over the atomic nucleus,

$$\bar{V} = -\frac{g_s^x g_N^p}{8 \pi m_N} \langle \sigma_N \rangle \cdot \left( \nabla \left( e^{-m_a r}/r \right) \right) \gamma^0. \quad (6)$$
Here, the quantity $\langle \sigma_N \rangle$ is proportional to the total angular momentum of the nucleus $I$

$$\langle \sigma_N \rangle = \kappa I/I.$$  

(7)

In the Schmidt (single-particle approximation) model, the nuclear-ground-state values of the coefficient $\kappa$ are $\kappa = +1$ for $^{129}$Xe and $\kappa = -1/3$ for $^{199}$Hg [19, 20] (see also Refs. [21, 22], which employ more sophisticated nuclear models). We point out that the spins of these nuclei are predominantly due to the spin of the unpaired valence neutron, irrespective of the nuclear model used. Thus, experimental measurements of EDMs of these atoms are mainly sensitive to the parameter $g_p^s$, which corresponds to the interaction of an axion with a neutron.

The potential (6) involves the Yukawa-type interaction which should be averaged over the nuclear density $\rho(R)$,

$$\langle e^{-m_a r}/r \rangle = \int d^3R e^{-m_a |r-R|/|R-R|} \rho(R).$$  

(8)

The nuclear density is well described by the Fermi function

$$\rho(R) = \frac{\rho_0}{1 + \exp \left( \frac{R-R_0}{a} \right)},$$  

(9)

where $R_0$ and $a$ are nucleus-dependent parameters and $\rho_0$ is normalized according to $\int \rho(R) d^3R = 1$. The values of these parameters for various isotopes are tabulated, e.g., in [24].

The interaction potential (6) induces an atomic EDM which in the leading order in perturbation theory reads

$$d = 2 \sum M \langle 0 | \bar{V} | M \rangle \langle M | \sigma \alpha | 0 \rangle / E_0 - E_M,$$  

(10)

where $e$ is the electron charge and the summation goes over the excited states $| M \rangle$ with energies $E_M$. We perform numerical calculations of the axion-exchange-induced EDMs of diamagnetic atoms using the relativistic Hartree-Fock-Dirac method including electron core polarization (RPA) corrections. The results are summarized in Table I. In this table, the results for an infinite axion mass are taken from [19], where the EDMs induced by the operator [4] were calculated.

### Table I. Summary of relativistic Hartree-Fock-Dirac calculations of atomic EDMs induced by the interaction (6) for various axion masses. These values are given in the units $C_{PS} \cdot e \cdot cm$, where $C_{PS} = -\sqrt{2} g_p^s g_n^p / (G_F m_a^2)$. These calculations take into account the effects of all atomic electrons. For axion masses $m_a \ll 1$ keV, the interaction (6) becomes long-range and the induced atomic EDMs become independent of $m_a$.

| $m_a$ (eV) | $^{129}$Xe | $^{199}$Hg | $^{211}$Rn | $^{226}$Ra |
|-----------|-----------|-----------|------------|-----------|
| $\infty$  | $1.6 \times 10^{-23}$ | $-1.8 \times 10^{-22}$ | $2.1 \times 10^{-22}$ | $-6.4 \times 10^{-22}$ |
| $10^8$    | $1.4 \times 10^{-23}$ | $-1.8 \times 10^{-22}$ | $1.7 \times 10^{-22}$ | $-5.2 \times 10^{-22}$ |
| $10^7$    | $3.6 \times 10^{-24}$ | $-3.7 \times 10^{-23}$ | $3.5 \times 10^{-23}$ | $-1.0 \times 10^{-22}$ |
| $10^6$    | $5.4 \times 10^{-25}$ | $-2.4 \times 10^{-24}$ | $2.1 \times 10^{-24}$ | $-5.4 \times 10^{-24}$ |
| $10^5$    | $8.9 \times 10^{-27}$ | $-2.7 \times 10^{-26}$ | $1.7 \times 10^{-26}$ | $-5.5 \times 10^{-26}$ |
| $10^4$    | $4.2 \times 10^{-29}$ | $-2.0 \times 10^{-28}$ | $1.5 \times 10^{-28}$ | $-4.5 \times 10^{-28}$ |
| $10^3$    | $1.1 \times 10^{-30}$ | $-1.0 \times 10^{-30}$ | $2.1 \times 10^{-30}$ | $-3.7 \times 10^{-30}$ |
| $10^2$    | $1.2 \times 10^{-32}$ | $-7.8 \times 10^{-33}$ | $2.3 \times 10^{-32}$ | $-3.1 \times 10^{-32}$ |
| $10^1$    | $1.2 \times 10^{-34}$ | $-7.8 \times 10^{-35}$ | $2.3 \times 10^{-34}$ | $-3.1 \times 10^{-34}$ |

The pink exclusion region in Fig. 1 has asymptotic regions at both low and high axion masses. For $m_a < 10^2$ eV, the constraint is $|g_p^s g_n^p| < 7 \times 10^{-17}$, while for $m_a > 10^5$ eV, the constraint is $|g_p^s g_n^p| < 3 \times 10^{-31} (m_a / eV)^2$. The latter constraint originates from the results of the paper [19], where the atomic EDMs due to the operator [4] were studied.

It is interesting to compare our results with earlier constraints from macroscopic-scale experiments [23, 25], which reported constraints on the coupling parameters $g_N^e g_n^e$, where $g_N^e$ denotes the axion coupling to a polarized neutron, while $g_n^e$ denotes the coupling to the nucleons in a non-polarized massive body. Let $\langle A \rangle$ and $\langle Z \rangle$ be the average atomic mass and proton numbers.
in the non-polarized massive body, respectively. Then, in general, the polarized neutron interacts with a non-polarized atom through the combination of constants \(g_N^p g_n^p\). The constraints on \(g_N^p g_n^p\) were obtained in \cite{25–29} with the assumption \(\langle A \rangle |g_N^p| \gg \langle Z \rangle |g_n^p|\), but we can assume the opposite case, \(\langle A \rangle |g_N^p| \ll \langle Z \rangle |g_n^p|\), to find the constraints on \(g_N^p g_n^p\). Since different experiments deal with different atoms, we approximate \(\langle A \rangle / \langle Z \rangle \approx 2.2\). This allows us to represent the results of the earlier works \cite{25–29} in the form of the gray exclusion region in Fig. 1. We conclude that our results give significantly improved limits on \(g_N^p g_n^p\) for \(m_a \gtrsim 10^{-2}\) eV.

Finally, we mention that limits on the nucleon-nucleon interaction constants \(g_N^p g_n^p\) have been derived from the consideration of the nuclear Schiff moments induced by the exchange of a low-mass axion-like particle between nucleons within a nucleus \cite{20}.

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