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W.C. Haxton

*Institute for Nuclear Theory, NK-12 and Department of Physics, FM-15
University of Washington, Seattle, WA 98195*

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Limits on CP Nonconserving Interactions from Electric Dipole Moments

W. C. Haxton

Institute for Nuclear Theory, HN-12 and Department of Physics, FM-15

University of Washington, Seattle, Washington 98195

Abstract:

I discuss bounds on CP-nonconserving (CPNC) and parity-nonconserving (PNC) hadronic interactions that result from measurements of atomic electric dipole moments. In most models of hadronic CPNC, the nuclear edm arises primarily from the polarization of the ground state by the CPNC PNC NN interaction, rather than from the edms of valence nucleons. When the atom is placed in an external field, the nucleus is fully shielded apart from nuclear finite size effects and relativistic corrections arising from hyperfine interactions, so that careful atomic calculations must be performed to deduce the residual sensitivity to the nuclear edm. I describe these shielding effects qualitatively, and present results from more detailed calculations. Atomic limits, when translated into effective bounds on the neutron edm, have now reached sensitivities that are comparable to direct neutron edm limits. I also discuss limits that can be extracted on CPNC parity-conserving (PC) hadronic interactions. Such interactions can generate atomic edms when combined with weak radiative corrections.

The possible time-reversal noninvariant (TRNI) and/or PNC static electromagnetic moments of elementary or composite particles can be easily categorized by recalling the transformation properties of the Coulomb, transverse electric, and transverse magnetic multipoles of rank J :

	<u>T</u>	<u>P</u>
CJ	$(-1)^J$	$(-1)^J$
EJ	$(-1)^{J+1}$	$(-1)^J$
MJ	$(-1)^{J+1}$	$(-1)^{J+1}$

It follows that the possible TRNI PNC, TRNI PC, and TRI PNC multipoles are

	<u>CJ</u>	<u>EJ</u>	<u>M5</u>
<u>TP</u>	C1,C3,...		M2,M4,...
<u>TP</u>		E2,E4,...	
<u>TP</u>		E1,E3,...	

The lowest of these in multipole rank, the electric dipole (C1) and anapole (E1) moments, can arise for spin-1/2 particles. They correspond to the nucleon current matrix elements

$$\langle p' | J_\mu^{em} | p \rangle_{\text{edm}} = d(q^2) \bar{u}(p') \sigma_{\mu\nu} q^\nu \gamma_5 u(p) \quad (1a)$$

$$\langle p' | J_\mu^{em} | p \rangle_{\text{anapole}} = a(q^2) \bar{u}(p') (q^2 \gamma_\mu - \not{q} q_\mu) \gamma_5 u(p) \quad (1b)$$

where $q_\mu = (p' - p)_\mu$.

The anapole, a TRI moment, will not be considered further. The edm and its M2 analog are the moments of interest.

If an intrinsic dipole exists (that is, a charge separation along the direction of the particle's spin $\vec{s}$), a torque can be applied to the particle by placing it in an external

electric field $\vec{E}$. The particle's spin will then precess, in analogy with the precession of a child's top in a gravitational field. The nonrelativistic Hamiltonian

$$H = d \vec{s} \cdot \vec{E} \quad (2)$$

corresponds to Eq. (1a), and is manifestly TRNI and PNC. The interest in electric dipole moments arises because of the extraordinary precision experimentalists have achieved. The present bound on the neutron edm from the measurements of the Grenoble [1] and Gatchina [2] groups is

$$|d_{\text{neutron}}| \leq 8 \cdot 10^{-26} \text{ e} \cdot \text{cm}, \quad 95\% \text{ c.l.} \quad (3)$$

while the recent measurements of the Seattle group [3] yielded

$$|d(^{199}\text{Hg})| \leq 1.3 \cdot 10^{-27} \text{ e} \cdot \text{cm}, \quad 95\% \text{ c.l.} \quad (4)$$

The following two comparisons may help one better appreciate these numbers. As atomic edm experiments often involve applied fields $\sim 10^4$ volts/cm, Eq. (4) corresponds to a shift in the ground state energy of ^{199}Hg of 10^{-23} eV, comparable to the interaction energy of two electrons separated by one light-month. Alternatively, if one were to magnify the ^{199}Hg atom until it was the size of the earth, the dipole bound would correspond to a charge excess at the north pole of depth 0.02 Å.

To constrain TRNI (or, equivalently, due to the CPT theorem, CPNC) interactions, we begin with a set of effective CPNC PNC meson-nucleon couplings, which later we will relate to an underlying model of CPNC interactions between quarks. (This is analogous to the usual treatment [5] of hadronic parity violation in the standard model, where weak PNC meson-nucleon couplings are related to the underlying exchanges of $\pi^\pm$ and Z^0 bosons between quarks.) From these couplings, one can estimate the nucleon edm from meson loops and derive a CPNC PNC NN interaction from meson exchange (with

one vertex being CPNC PNC and the other strong). The nuclear edm is then the result of the edms of unpaired valence nucleons and of the polarization of the nuclear ground state by the CPNC PNC NN interaction. The nuclear edm then induces a CPNC PNC interaction between the nucleus and atomic electrons that polarizes the atomic cloud. The applied field can couple to the atom through the polarization amplitude as well as through the direct coupling to nuclear edm, as illustrated in Fig. 1. This response can then be compared to that measured by the experimentalists.

In the standard model there are two sources of CPNC and PNC interactions, the phase in the Kobayashi-Maskawa matrix and the $\bar{\theta}$ term in the QCD Lagrangian [6]. The latter has the form

$$\bar{\theta} \frac{g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \quad (5)$$

where $F_{\mu\nu}$ is the gluon field tensor and $\tilde{F}^{\mu\nu}$ its dual. The neutron edm bound requires $|\bar{\theta}| \lesssim 10^{-10}$. The unnaturalness of such a small coupling in a strong interaction Lagrangian is commonly called the strong CP problem. We will use $\bar{\theta}$ to illustrate how experiments on atomic edms limit CPNC PNC interactions.

As Crewther *et al.* [7] showed, one consequence of $\bar{\theta}$ is the generation of a CPNC PNC scalar coupling of the pion to the nucleon of strength $\bar{g}_{\pi NN}^0 \sim 0.03 \bar{\theta}$,

$$\mathcal{L}_{\pi NN} = \vec{\pi} \cdot \vec{N} \vec{\tau} (i\gamma_5 g_{\pi NN} + \bar{g}_{\pi NN}^0) N$$

where $g_{\pi NN}$ is the usual strong coupling. As the pion is the lightest charged meson, one might expect the associated pion loop of Fig. 2 to make an important contribution to the neutron edm. The result [7]

$$d_n = e g_{\pi NN} \frac{\bar{g}_{\pi NN}^0}{4\pi^2 M} \ln \left(\frac{M}{m_\pi} \right) \quad (6)$$

is, in fact, the leading term by virtue of the logarithm. Equation (3) then yields $|\bar{\theta}| \lesssim 2 \cdot 10^{-10}$. The corresponding CPNC PNC NN interaction [8] involves the emission of a

pion by one nucleon through the $\bar{g}_{\pi NN}^0$ vertex and its reabsorption by a second through $g_{\pi NN}$.

As the most general CPNC PNC πNN vertex [9] involves three possible isospin couplings,

$$\bar{g}_{\pi NN}^0 \bar{N} \vec{\tau} N \cdot \vec{\pi} \quad (7a)$$

$$\bar{g}_{\pi NN}^1 \bar{N} N \pi_0 \quad (7b)$$

$$\bar{g}_{\pi NN}^2 \bar{N} (3\tau_z \pi^0 - \vec{\tau} \cdot \vec{\pi}) N \quad (7c)$$

the QCD $\bar{\theta}$ term has rather simple nuclear/nucleon physics consequences even in the context of meson-exchange models limited to pionic interactions.

The nuclear edm then arises from the two terms illustrated in Fig. 3. The external electric field can couple to the edm of a valence nucleon, or it can virtually excite the nucleus by the action of the ordinary C1 operator on the ground state. In the latter case, the edm results from the depolarization of the nucleus by the CPNC PNC NN interaction. Clearly the polarizability illustrated in Fig. 3 is complicated, requiring a summation over a complete set of intermediate nuclear states. The polarizability is also generally the dominant contribution to the nuclear edm [8,10]. That is, the nuclear edm is a many-body quantity with a magnitude that generally exceeds that of a single nucleon.

The effect of the polarizing CPNC PNC NN interaction can often be envisioned in terms of an effective one-body potential [8,9], which one can obtain by averaging the two-body potential over a closed nuclear core. Such averaging shows that the polarizing potential that distorts the orbits of valence nucleons is coherent over core nucleons. In the case of $\bar{\theta}$, valence protons and neutrons in identical orbits cancel against each other, so that the residual effect is proportional to $(N - Z)/A$ [8]. That is, it is produced by the neutron excess. In other models (e.g., the KM model) $\bar{g}_{\pi NN}^1$ is nonzero, and the

contributions of core neutrons and protons do not cancel.

While in ordinary nuclei the polarization sum is dominated by the giant E1 resonance residing 10-20 MeV above threshold, there are special nuclei with chance ground state opposite parity doublets. Such nuclei can exhibit enhanced polarizabilities, and thus enhanced dipole moments. Several examples that Henley and I found [9] are shown in Table 1. The resulting polarization contributions to the nuclear edm are $10^2 - 10^4$ times that of valence nucleons. As these nuclei do not have atomic clouds with $\vec{s}_e = 0$, the experimental technique [3] applied to ^{199}Hg unfortunately cannot be used. However, as new, more general experimental procedures are being developed [11], perhaps such enhancement factors might be exploited in the future.

Atomic screening corrections are very important when one attempts to probe a nuclear edm within a neutral atom. A theorem due to Schiff [12] states that for a point nucleus and an atom that is held together by the Coulomb force, the interaction energy in an external electric field linear in the electric dipole moment vanishes. This can be understood classically. As the atom is neutral, it does not accelerate when the electric field is applied. The nucleus carries a charge but, being fixed within the atom, also does not accelerate. For this to be the case, the net electric field at the nucleus must be zero: the polarization of the atom is such that the sum of the external field plus that of the sagging atomic cloud vanishes at the nucleus. This is illustrated in Fig. 1. This theorem will be evaded to the extent that the finite atomic size allows electron penetration, which prevents complete shielding. The penetration terms lead to a residual electron-nucleus contact interaction

$$H_{edm}^{e-p} = -4\pi e Q \frac{\langle \vec{I} \rangle}{I} \cdot \vec{\nabla} \delta(\vec{x}) \quad (8a)$$

$$\vec{Q} = \langle r^2 \vec{d} \rangle - \frac{5}{3} \langle r_p^2 \rangle \langle \vec{d} \rangle \quad (8b)$$

where $Q = \langle JJ | \vec{Q} | JJ \rangle$. Here $\langle \vec{d} \rangle$ is the nuclear dipole moment, and $\langle r_p^2 \rangle$ and $\langle r^2 \vec{d} \rangle$ are the r^2 -weighted moments of the charge and electric dipole distributions. Q

is known as the Schiff moment. Eq. (8a) is valid for s-p atomic mixing, the only case of interest.

In addition to the Schiff moment, two other effects may contribute to the measured atomic edm. Relativistic contributions are generated by the hyperfine interactions of the atomic cloud with the nuclear magnetic dipole and electric quadrupole moments. To the extent that these modify the energy of the electron-hole bubble in the polarization graph of Fig. 1, the Schiff cancellation is incomplete. There also exists a polarization graph, similar to that of Fig. 1 but with the $C1 \cdot C1^{CPNC}$ interaction replaced by $M2 \cdot M2^{CPNC}$, where $M2^{CPNC}$ is the CPNC M2 moment: the distortion of the atomic cloud by the external field produces the spatially inhomogeneous field needed to interact with this higher moment.

In ^{199}Hg the Schiff cancellation leads to a suppression of the interaction energy (relative to that of a bare edm) by a factor of 10^{-3} [10]. For light nuclei the suppression is much higher, $\sim 10^{-9}$ for ^4He [12]. Heavy nuclei are favored because the large Z greatly enhances the electron penetration. Relativistic effects compete with the Schiff moment only in light nuclei. Thus we have not included them in our ^{199}Hg calculation, though an effect due to the nuclear magnetic moment of ^{199}Hg does exist. There is no M2 contribution because ^{199}Hg has a ground state spin of $1/2$.

To deduce a bound on $\bar{g}_{\pi NN}$ from the ^{199}Hg edm limit of Jacobs *et al.* two calculations are required. An atomic physics calculation that includes the effective interaction of Eq. (8) must be done to determine the maximum value of the Schiff moment that is consistent with experiment. Khriplovich, Flambaum, and Sushkov [10] and Jacobs *et al.* [3] find

$$|Q(^{199}\text{Hg})| \leq 3.2 \cdot 10^{-11} f^3 \quad 95\%c.l.$$

This must be compared to a nuclear physics calculation of Q , or equivalently, the nuclear edm distribution $\vec{d}(r)$. One such calculation, involving one-body approximations to

the polarization contribution, is quoted in Ref. [3]. Kar Lee and I [13] have recently completed a somewhat more realistic calculation using Nilsson model wave functions (with deformation parameter $\delta = -0.1$) to describe the spectrum of states in ^{199}Hg . The dipole distributions $\vec{d}(r)$ and $r^2\vec{d}(r)$ depend on the one-body contribution (generated by the unpaired valence nucleon) and on the polarization contribution. As the Nilsson model wave functions are expanded in a harmonic oscillator basis, the polarizability involves a large but finite sum: $r^2\vec{d}(r)$ connects excitations split by one and three oscillator shells.

We can extract bounds on $\bar{g}_{\pi NN}^0$, $\bar{g}_{\pi NN}^1$, and $\bar{g}_{\pi NN}^2$ or, equivalently, on the neutron edm allowed for a specific model. In the case of $\bar{\theta}$ the calculations reported in Ref. [3] give $|d_n^{\bar{\theta}}| < 17 \cdot 10^{-26}$ e-cm, which can be compared to the neutron result given in Eq. (3). While the atomic bound is less restrictive, the chosen model is not the most favorable one for atomic tests: we noted earlier that the CPNC PNC NN potential for $\bar{\theta}$, when averaged over core nucleons, is reduced by a factor of $(N - Z)/A$ due to the cancellation between core protons and neutrons. Comparisons for other models of CPNC generally show that the ^{199}Hg and neutron bounds are comparable [3]. In the case of the more complete calculations that Lee and I have performed, the atomic bound on $|d_n^{\bar{\theta}}|$ is weakened by about a factor of three. This result is still preliminary.

The future for atomic tests looks very bright. The recent measurement of Jacobs *et al.* [3] improved the ^{199}Hg bound by a factor of 20, and a similar improvement is the goal of their next experiment [14]. New experimental techniques may allow one to use $\vec{s}_e \neq 0$ targets and thus nuclei with enhanced polarizabilities. Such targets are also required for probing CPNC PNC M2 nuclear moments, which can make large contributions to atomic edms. There is considerable hope that much of the region between the present bounds and d_n values characteristic of the KM phase ($\sim 10^{-31}$ e-cm) can be explored in the next decade. This is the region where new sources of CP violation may be

discovered.

I will briefly mention some related work [15] on TRNI PC hadronic interactions. These are very exotic theoretically: it has been argued that flavor-conserving TRNI (or CPNC) PC interactions do not arise in renormalizable gauge theories in first order in the boson exchanges between fermions [16]. However, the experimental constraints on such interactions are very weak: compound nucleus studies [17] of detailed balance and nuclear energy level fluctuations have yielded $\alpha \lesssim 2 \cdot 10^{-3}$, where α measures the magnitude of typical TRNI PC nuclear matrix elements relative to that of the strong interaction. A neutron transmission experiment [18] measuring the TRNI PC five-fold correlation $\vec{\sigma} \cdot (\vec{k} \times \vec{I})(\vec{k} \cdot \vec{I})$, where $\vec{\sigma}$ and $\vec{k}$ are the neutron spin and momentum and $\vec{I}$ is the nuclear spin, produced a similar limit, $\alpha \lesssim 5 \cdot 10^{-3}$.

Such interactions, when combined with weak radiative corrections, can generate edms: the weak interaction provides the needed parity violation. Thus one can extract limits on α from the bounds on atomic and neutron edms. We have recently completed an investigation [15] of “long-distance” contributions to such induced edms: the TRNI PC and weak TRI PNC interactions are separated by states involving hadronic distance scales typical of meson exchange. The starting point was a TRNI PC ρNN vertex analogous to Eqs. (7), as Simonius [19] showed that ρ -exchange generated the longest range TRNI PC NN interaction. If one characterizes the strength of such a potential relative to strong ρ exchange by $\bar{g}_\rho$, α and $\bar{g}_\rho$ are crudely related by

$$\alpha \sim \bar{g}_\rho \frac{k_F^2}{m_\rho^2}$$

where k_F is the nuclear Fermi momentum. The k_F^2/m_ρ^2 suppression is a general feature of TRNI PC meson-exchange potentials: the lowest allowed partial wave amplitudes are $^1P_1 \leftrightarrow ^3P_1$ and $^3S_1 \leftrightarrow ^3D_1$ [19].

A. Höring, M. Musolf, and I considered [15] three mechanisms shown in Fig. 4, the loop contribution to the nucleon edm, the atomic edm generated by Z^0 exchange

between the nucleus and the atomic electrons, and the nuclear edm generated by the Simonius ρ potential combined with the weak hadronic interaction. The resulting limits on α are

$$\alpha \leq 10^{-5} \left\{ \begin{array}{ll} 0.6 \left| \frac{f_{\pi}^{DDH}}{f_{\pi}} \right| & \text{neutron} \\ 11 & {}^{199}\text{Hg, atomic PNC} \\ 13 & {}^{199}\text{Hg, nuclear PNC} \\ \left| 0.46 \left(\frac{\lambda_{\rho}^0}{\lambda_{\rho}^{DDH}} \right) + 0.54 \left(\frac{f_{\pi}^{DDH}}{f_{\pi}} \right) \right| & \end{array} \right.$$

where f_{π} and h_{ρ}^0 are the PNC weak πNN and isoscalar ρNN couplings and the superscripts DDH denote the standard model “best values” for these couplings [5]. We see that the constraints from such long-range edm mechanisms are a factor of ~ 100 more restrictive than those extracted from compound nucleus studies.

Recently Conti and Khriplovich [20] have argued that short-ranged two-loop contributions to edms provided considerably more stringent bounds on TRNI PC interactions. The comparison of this work to that of Ref. [15] is discussed in Ref. [15].

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Table I. Examples of nuclei where chance ground state opposite parity doublets can produce enhanced polarizabilities and thus enhanced electric dipole and magnetic quadrupole moments. The energy splitting of the doublet is given, along with the edm and M2 moments in units of the corresponding moments of the unpaired valence nucleon. The calculations were done in a Nilsson model [9].

<u>Nucleus</u>	<u>$\Delta E(keV)$</u>	<u>D_N/d_n</u>	<u>$M2/m2$</u>
^{153}Sm	35.8	86	10
^{225}Ac	40.0	19	610
^{229}Pa	0.22	2390	12,400

Figure Captions

Figure 1. Diagrams representing the interaction of an external electric field with the nuclear edm and with an electron particle-hole excitation induced by the interaction of the atomic cloud with the nuclear edm. The sum can be represented by a polarization graph where the electron-nucleus interaction is a contact interaction.

Figure 2. A pion loop contribution to the nuclear edm.

Figure 3. Contributions to the nuclear edm due to a) the edm of a valence nucleon and b) the nuclear polarizability induced by a CPNC PNC NN potential. The nuclear Green's function is denoted by G_0 .

Figure 4. Schematic representation of a) the π - ρ loop contribution to the neutron edm, b) the atomic edm generated by Z^0 exchange between the electrons and nucleons in combination with a TRNI PC ρ potential in the nucleus, and c) the nuclear edm generated by the polarization of the nucleus by a TRNI PC ρ potential and by the PNC weak hadronic interaction.

Figure 1

Figure 2

Figure 3

Figure 4

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