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Nucleon electric dipole moments and the isovector parity- and time-reversal-odd pion–nucleon coupling

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ABSTRACT

The isovector time-reversal- and parity-violating pion–nucleon coupling $\bar{g}_\pi^{(1)}$ is uniquely sensitive to dimension-six interactions between right-handed light quarks and the Standard Model Higgs doublet that naturally arises in left-right symmetric models. Recent work has used the $\bar{g}_\pi^{(1)}$-induced one-loop contribution to the neutron electric dipole moment d_n, together with the present experimental d_n bound, to constrain the CP-violating parameters of the left-right symmetric model. We show that this and related analyses are based on an earlier meson theory d_n computation that is not consistent with the power-counting appropriate for an effective field theory. We repeat the one-loop calculation using heavy baryon chiral perturbation theory and find that the resulting d_n sensitivity to $\bar{g}_\pi^{(1)}$ is suppressed, implying more relaxed constraints on the parameter space of the left-right symmetric model. Assuming no cancellations between this loop contribution and other contributions, such as the leading order EDM low-energy constant, the present limit on d_n implies $|\bar{g}_\pi^{(1)}| \lesssim 1.1 \times 10^{-10}$.

1. Introduction

Electric dipole moments (EDMs) of neutral atoms, molecules, and the neutron provide sensitive probes of new sources of time-reversal (T) and parity (P) violation. Current upper limits on the EDMs of the ^{199}Hg atom [1], $d_A(^{199}\text{Hg})$, and neutron [2], d_n, place tight constraints on the QCD vacuum angle within the Standard Model (SM) as well as on possible sources of sources of CP-violation (CPV) arising from physics beyond the SM (BSM).[1] The existence of BSM CPV is needed in order to explain the cosmic baryon asymmetry (for a recent review, see Ref. [3]). If the asymmetry had been generated at temperatures of order of the electroweak (EW) scale, then d_n provides a particularly sensitive probe.

At energies below the scale of BSM interactions Λ but above the EW scale, one may characterize the effects of BSM CPV interactions in terms of an effective theory involving only SM fields:

$$\mathcal{L}_{\text{CPV}} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\text{BSM}}^{\text{eff}}, \tag{1}$$

where $\mathcal{L}_{\text{CKM}}$ and $\mathcal{L}_{\bar{\theta}}$ denote the SM Cabibbo–Kobayashi–Maskawa (CKM) [4] and QCD vacuum angle [5–7] CPV Lagrangians, respectively, and

$$\mathcal{L}_{\text{BSM}}^{\text{eff}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(6)} \mathcal{O}_i^{(6)} + \cdots \tag{2}$$

gives the set of non-renormalizable CPV effective operators at the weak scale $v = 246$ GeV generated by BSM physics at a scale $\Lambda > v$. For brevity, we have indicated only those entering at dimension (d) six, while the $+\cdots$ indicate those of higher dimension.[2] Among the more widely considered $d = 6$ CPV operators are the elementary fermion EDMs, the quark chromo-EDMs, and the Weinberg three-gluon operator.

In this study, we focus on one particular $d = 6$ operator that naturally arises in left-right symmetric model (LRSM) extensions of the SM, that gives rise to EDMs of nucleons, nuclei, and diamagnetic atoms, and that has received considerably less attention

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[1] In what follows, we assume CPT conservation, so that the signal for a non-vanishing neutron EDM would also indicate the presence of CP-violation.

[2] A complete list of dimension six operators may be found in Ref. [8], while those directly relevant to EDMs are listed in Tables 3 and 4 of Ref. [9].

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than the other operators that arise at this order in the effective theory:

$$\mathcal{O}_{\varphi ud} = i\left(\tilde{\varphi}^{\dagger} D_{\mu}\varphi\right)\bar{u}_R \gamma^{\mu} d_R, \tag{3}$$

where φ is the Higgs doublet, $\tilde{\varphi} = i\tau_2\varphi^*$, D_{μ} is the $SU(2)_L \times U(1)_Y$ covariant derivative and u_R (d_R) is the right-handed up-quark (down-quark) field. In LRSMs, the corresponding Wilson coefficient $C_{\varphi ud}$ is generated by mixing between the left- and right-handed W bosons in the presence of either spontaneous CPV and/or explicit CPV in the right-handed quark CKM matrix.

After electroweak symmetry-breaking wherein $\varphi^T \to (0, v/\sqrt{2})$, the exchange of the $W^{\pm}$ contained in the covariant derivative with a left-handed quark current leads to an effective four quark interaction[3]

$$\mathcal{L}^{\text{eff}}_{\text{LR,CPV}} = -i\frac{\operatorname{Im} C_{\varphi ud}}{\Lambda^2}\left[\bar{d}_L\gamma^{\mu}u_L\bar{u}_R\gamma_{\mu}d_R - \bar{u}_L\gamma^{\mu}d_L\bar{d}_R\gamma_{\mu}u_R\right]. \tag{4}$$

The interaction in Eq. (4) breaks isospin symmetry, thereby giving rise to, among other interactions, the isovector TVPV πNN interaction:

$$\mathcal{L}^{\text{TVPV}}_{\pi N, I=1} = \bar{g}^{(1)}_{\pi}\bar{N}\pi^0 N, \tag{5}$$

where N and π^0 are the nucleon and neutral pion fields, respectively. This interaction leads to long-range contributions to the nuclear Schiff moment that induces $d_A(^{199}\text{Hg})$ as well as long-range contributions to d_n that can be computed in chiral perturbation theory. The present limits on these EDMs, thus, imply constraints on the mass M_{W_R} of the right-handed W-boson and associated CPV phases in the LRSM.

Following this line of reasoning, the authors of Refs. [11,12] have derived constraints on M_{W_R} and the strength of spontaneous CPV in the LRSM from the limits on d_n and the corresponding implications of CPV in the neutral kaon sector. The results imply that $M_{W_R} > 10$ TeV. In related work, the authors of Ref. [13] observed that $\mathcal{O}_{\varphi ud}$ will also induce a semi-leptonic CPV operator that contributes to neutron decay. Even without specifying to the LRSM, the d_n limits on $C_{\varphi ud}$ then constrain the magnitude of possible effects in T-odd neutron decay correlations. In both cases, the d_n constraints relied on an earlier pion-loop calculation performed by the authors of Ref. [14] using a relativistic meson–nucleon field theory approach. The results indicate that the leading term in d_n resulting from the interaction (5) is proportional to the neutron anomalous magnetic moment κ_n and is independent of the pion-to-nucleon mass ratio, m_{π}/m_N. From the standpoint of effective field theory (EFT), this result is surprising, as the anomalous magnetic moment vertex brings in an inverse power of the nucleon mass while consistent power counting in chiral perturbation theory requires that loops only bring in momenta of order of the pion mass. The absence of any m_{π}/m_N suppression in the computation of Ref. [14] is not consistent with this expectation.

In what follows, we repeat the pion loop computation associated with (5) using heavy baryon chiral perturbation theory (HBChPT) [15] and show that the result proportional to $\bar{g}^{(1)}_{\pi}\kappa_n$ is suppressed by $(m_{\pi}/m_N)^2 \sim 0.02$. HBChPT implements the power counting required by an EFT by expanding about both the static nucleon ($m_N \to \infty$) and chiral ($m_{\pi} \to 0$) limits. Our results imply considerably weaker constraints on $C_{\varphi ud}$ from the long-range contribution to d_n than obtained in the studies of Refs. [11–13]. Presently uncalculable short-distance contributions associated with loop momenta of order one GeV that reside in the nucleon EDM counterterm may imply stronger constraints as suggested by naïve dimensional analysis (NDA). In this context, one may view the relativistic meson theory computation of Ref. [14] as providing a model estimate of the short-distance contributions. Generally speaking, however, both the sign and magnitude of NDA and/or model estimates for the short distance contributions are subject to uncertainty, so the most conservative implications will be inferred from the calculable long-distance terms.

In this respect, we note that the diamagnetic EDMs provide an in principle more robust benchmark than d_n, as the nuclear Schiff moment arises from tree-level pion exchange between two nucleons and is relatively free from the uncertainties associated with short-distance contributions. In practice, the many-body nuclear theory uncertainty associated with the interaction (5) are substantial [9], with the situation for ^{199}Hg being particularly unsettled. Looking to the future, storage-ring searches for EDMs of light nuclei such as the deuteron or ^{3}He nucleus [16] would provide theoretically cleaner probes of $\mathcal{O}_{\varphi ud}$ since the short-distance contributions to such EDMs are relatively minor and since the few-body nuclear theory is well under control [17]. In the immediate term, however, the long-range contribution to d_n appears to be the most trustworthy avenue for accessing $\mathcal{O}_{\varphi ud}$.

In the remainder of this paper, we discuss the details of our calculation. In Section 2 we summarize the HBChPT framework as it applies to the computation of TVPV observables and give the details of our nucleon EDM computation. In Section 3 we compare our results with those of Ref. [14]. We discuss the implications and summarize in Section 4.

2. HBChPT calculation

Loop computations performed with a relativistic meson–nucleon field theory and dimensional regularization include explicit contributions from loop momenta of order m_N, thereby eliminating the possibility of a consistent power counting.[4] In HBChPT [15], one removes these contributions by first redefining the nucleon degrees of freedom in terms of heavy fields having fixed velocity v

$$N_v = \frac{1+\not{v}}{2}e^{im_N v\cdot x}N, \tag{6}$$

where

$$p^{\mu} = m_N v^{\mu} + k^{\mu}, \tag{7}$$

with k being a residual momentum. We henceforth omit the "v" subscript. Derivatives acting on the heavy fields give the small residual momenta, and the propagator of a heavy-nucleon field no longer contains the nucleon mass. The results of loop integrals involving the N fields then scale with powers of Q/m_N and Q/Λ_{χ}, where Q is of order m_{π} or the external momentum (assumed to be well below one GeV), $\Lambda_{\chi} = 2\pi F_{\pi}$ is the scale of chiral symmetry breaking, and $F_{\pi} = 186$ MeV is the pion decay constant.[5] One, thus, obtains a consistent EFT power counting.

The HBChPT interactions are constructed from the heavy nucleon and pion fields, the velocity v^{μ}, and the spin S^{μ} with $S = (\vec{\sigma}/2, 0)$ in the nucleon rest frame $v = (\vec{0}, 1)$. It is also useful to project vectors in their components parallel and orthogonal to the velocity. We use a subscript $\perp$ to denote the perpendicular components. For example, the perpendicular covariant derivative is

$$\mathcal{D}^{\mu}_{\perp} = \mathcal{D}^{\mu} - v^{\mu}v\cdot\mathcal{D}. \tag{8}$$

[3] Corrections due to the evolution of the four quark interaction to hadronic scales are minor, see the discussion in Ref. [10].

[4] A relativistic approach can provide a reliable power counting if more complicated regularizations schemes are applied, for a review see Ref. [18].

[5] Note that other work in HBChPT uses $f_{\pi} = F_{\pi}/2$.