Annals of Physics 338 (2013) 50–96

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

The effective chiral Lagrangian from dimension-six parity and time-reversal violation

J. de Vries [a,b,*], E. Mereghetti [c], R.G.E. Timmermans [a], U. van Kolck [d,e]

[a] KVI, Theory Group, University of Groningen, 9747 AA Groningen, The Netherlands
[b] Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
[c] Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA
[d] Institut de Physique Nucléaire, Université Paris Sud, CNRS/IN2P3, 91406 Orsay, France
[e] Department of Physics, University of Arizona, Tucson, AZ 85721, USA

HIGHLIGHTS

- Classification of T-odd dimension-six sources based on impact on observables.
- Building of the chiral Lagrangian for each dimension-six source.
- Calculation of the PT-odd pion–nucleon form factor for each source.
- Discussion of hadronic EDMs for each source and comparison with the theta term.

ARTICLE INFO

Article history:
Received 19 December 2012
Accepted 3 May 2013
Available online 19 July 2013

Keywords:
CP violation
Time-reversal violation
Chiral effective field theory
Electric dipole moments
Dimension-six operators

ABSTRACT

We classify the parity- and time-reversal-violating operators involving quark and gluon fields that have effective dimension six: the quark electric dipole moment, the quark and gluon chromo-electric dipole moments, and four four-quark operators. We construct the effective chiral Lagrangian with hadronic and electromagnetic interactions that originate from them, which serves as the basis for calculations of low-energy observables. The form of the effective interactions depends on the chiral properties of these operators. We develop a power-counting scheme and calculate within this scheme, as an example, the parity- and time-reversal-violating pion–nucleon form factor. We also discuss the electric dipole moments of the nucleon and light nuclei.

* Corresponding author at: KVI, Theory Group, University of Groningen, 9747 AA Groningen, The Netherlands. Tel.: +31 645756008.

E-mail addresses: devries.jordy@gmail.com, devries@kvi.nl (J. de Vries).

0003-4916/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.aop.2013.05.022

1. Introduction

The Standard Model (SM) of particle physics contains, in its minimal version, two sources of time-reversal (T), or, equivalently, CP violation. In the electroweak sector, the phase in the quark mixing matrix [1] is associated with the Jarlskog parameter $J_{\rm CP} \simeq 3 \times 10^{-5}$ [2]. The strong sector contains the QCD vacuum angle $\bar{\theta}$ [3], but the experimental upper limit on the neutron electric dipole moment (EDM) shows that $\bar{\theta}$ is unnaturally small, $\bar{\theta} \lesssim 10^{-10}$ [4]. CP violation within the SM is believed to be insufficient for a successful baryogenesis scenario [5], and therefore new sources of CP violation are expected in order to explain the cosmological matter–antimatter asymmetry. This is not a surprise since the SM is likely but the dimension-four part of an effective field theory (EFT) that contains higher-dimensional operators, some of which will violate CP.

Powerful probes of such CP violation beyond the SM are EDMs of nucleons, nuclei, atoms, and molecules [6,7], which violate both parity and time reversal ($\not{P}\not{T}$). Since the SM predictions from the quark mixing matrix [8] are orders of magnitude away from current experimental limits, a finite EDM in upcoming experiments would be an unambiguous sign of new physics. In addition to impressive improvements [9] on the time-honored EDM experiments with neutrons and neutral atoms, in particular ^{199}Hg, which have resulted in very precise limits [10,11], novel ideas exist for the measurement of EDMs of charged particles, such as the proton, deuteron and helion, in storage rings [12]. An important question that comes up is whether, when future experiments measure nonzero EDMs, we will be able to pinpoint the microscopic source of P and T violation.

EDMs of strongly interacting particles arise from the higher-dimensional $\not{P}\not{T}$ operators at the quark–gluon level. These non-renormalizable operators might have their origin in a renormalizable theory at a higher-energy scale, such as, for example, supersymmetric (SUSY) extensions of the SM. At the SM scale, the most important higher-dimensional $\not{P}\not{T}$ operators should be those of dimension six, as we are not concerned here with CP violation in the dimension-five leptonic operator [13] that gives rise to neutrino masses and mixings. From symmetry considerations it is found [14–17] that the following flavor-diagonal $\not{P}\not{T}$ operators appear at an effective dimension six: the quark electric dipole moment (qEDM) [18], which couples quarks and photons; the quark chromo-electric dipole moment (qCEDM) [19], which couples quarks and gluons; the Weinberg operator [20], which couples three gluons and gives rise to a gluon chromo-electric dipole moment (gCEDM) [21], and four four-quark operators [16,22].

Since it is not feasible to calculate hadronic and nuclear properties directly from a Lagrangian at the quark–gluon level, we use chiral EFT [23] – a generalization to more than one nucleon of chiral perturbation theory (χPT) [24,25] – to translate microscopic operators into operators that include nucleons, pions, and photons. (For reviews, see Refs. [26–29].) After the translation, we are able to calculate hadronic properties directly from the effective Lagrangian. For the dimension-four $\bar{\theta}$ term, this method was first employed in Ref. [4], and later extended in the context of $SU(2) \times SU(2)$ [30–40] and of $SU(3) \times SU(3)$ [41,42] χPT.

In this paper we extend the method further to include dimension-six operators in the framework of $SU(2) \times SU(2)\chi$PT. (Generalization to $SU(3) \times SU(3)$ is straightforward.) The effective chiral Lagrangian includes not only interactions that stem from spontaneous chiral-symmetry breaking and are therefore chiral invariant, but also interactions that break chiral symmetry in the same way as chiral-symmetry-breaking operators at the QCD level. Since the dimension-six operators break chiral symmetry differently from each other and from the $\bar{\theta}$ term, they will generate different low-energy hadronic interactions. Given enough observables it should be thus possible to separate the various $\not{P}\not{T}$ sources.

In addition to constructing the Lagrangian, we need to organize in leading order (LO), next-to-leading order (NLO), *etc.* the various effective $\not{P}\not{T}$ operators that appear. This is done according to the estimated size of their contributions to observables. In order to get a consistent, manifest power counting we work in the heavy-baryon framework [43] wherein the nucleon mass has been eliminated from the nucleon propagator. This framework has a transparent power counting and greatly simplifies loop calculations, but there are some complications when one goes to subleading orders in the Lagrangian. These problems can be solved by demanding that the Lagrangian obeys reparametrization invariance (RPI) [44]. This puts constraints on certain coefficients of operators, which we construct up to NNLO.