Physics Letters B 665 (2008) 168–172

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Nuclear electric dipole moment of ^{3}He

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ARTICLE INFO

Article history:
Received 23 April 2008
Received in revised form 2 June 2008
Accepted 13 June 2008
Available online 18 June 2008
Editor: J.-P. Blaizot

PACS:
11.30.Er
21.10.Ky
21.60.De
21.60.Cs

Keywords:
Time-reversal and parity violation
Nucleon–nucleon interactions
Electric dipole moments

ABSTRACT

A permanent electric dipole moment (EDM) of a physical system requires time-reversal (T) and parity (P) violation. Experimental programs are currently pushing the limits on EDMs in atoms, nuclei, and the neutron to regimes of fundamental theoretical interest. Here we calculate the magnitude of the P-, T-violating EDM of ^{3}He and the expected sensitivity of such a measurement to the underlying P-, T-violating interactions. Assuming that the coupling constants are of comparable magnitude for π-, ρ-, and ω-exchanges, we find that the pion-exchange contribution dominates. Our results suggest that a measurement of the ^{3}He EDM is complementary to the planned neutron and deuteron experiments, and could provide a powerful constraint for the theoretical models of the pion–nucleon P-, T-violating interaction.

1. Introduction

A permanent electric dipole moment (EDM) of a physical system would indicate direct violation of time-reversal (T) and parity (P) and thus CP violation through the CPT invariance. Presently there are several experimental programs pushing the limits on EDMs in atoms, nuclei, and the neutron to regimes of fundamental interest. The Standard Model (SM) predicts values for the EDMs of these systems that are too small to be detected in the foreseeable future, and hence a measured nonzero EDM in any of these systems is an unambiguous signal for a new source of CP violation and for physics beyond the SM. A new experimental scheme [1–5] for measuring EDMs of nuclei (stripped of their atomic electrons) in a magnetic storage ring suggests that the EDM of the deuteron could be measured to an accuracy of better that 10^{-27} $e\,$cm [4]. Unlike searches for CP-violating moments of the nucleus through measurements of atomic EDMs, a measurement for a stripped nucleus would not suffer from a suppression of the signal through atomic Schiff screening [6]. For this reason, the latter could represent about an order of magnitude better sensitivity to the underlying CP-violating interaction than the present limit on the neutron EDM, d_n [2]. Measurements using stripped nuclei in a magnetic storage ring are best suited to nuclei with small magnetic anomaly, making ^{3}He an ideal candidate for a high precision measurement. Here we examine the nuclear structure issues determining the EDM of ^{3}He and calculate the matrix elements of the relevant operators using the no-core shell model [7] and Podolsky's method for implementing second-order perturbation theory [8]. An approximate and incomplete calculation for the ^{3}He dipole exists in the literature [9], but here we present much more reliable calculations based on an exact solution of the three-body problem using several potential models for the nucleon–nucleon (NN) interaction, complemented with three-body forces.

2. Sources of nuclear *P*-, *T*-violation

A nuclear EDM consists of contributions from the following sources: (i) the intrinsic EDMs of the proton and neutron, d_p and d_n; (ii) the polarization effect caused by the P-, T-violating ($\not P \not T$) nuclear interaction, $H_{\not P \not T}$; (iii) the two-body $\not P \not T$ meson-exchange charge operator appropriate for $H_{\not P \not T}$.

The contribution due to nucleon EDMs, $D^{(1)}$, which is purely one-body, can be easily evaluated by taking the matrix element

$$D^{(1)} = \langle\psi|\sum_{i=1}^{A}\frac{1}{2}\big[(d_p + d_n) + (d_p - d_n)\tau_i^z\big]\sigma_i^z|\psi\rangle, \tag{1}$$

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doi:10.1016/j.physletb.2008.06.019

where $|\psi\rangle$ is the nuclear state that has the maximal magnetic quantum number. In the particular case of interest in this Letter, $|\psi\rangle = |0\rangle$ is the ground state of ^{3}He obtained by the diagonalization of the P-, T-conserving interaction.

In perturbation theory $H_{\not P \not T}$ induces a parity admixture to the nuclear state

$$|\tilde{0}\rangle = \sum_{n\neq 0} \frac{1}{E_0 - E_n} |n\rangle\langle n|H_{\not P \not T}|0\rangle, \tag{2}$$

where $|n\rangle$ are eigenstates of energy E_n and opposite parity from $|0\rangle$, which are calculated with the P-, T-conserving Hamiltonian. Hence, the polarization contribution $D^{(\mathrm{pol})}$ can be simply calculated as

$$D^{(\mathrm{pol})} = \langle 0|\hat{D}_z|\tilde{0}\rangle + \text{c.c.}, \tag{3}$$

where

$$\hat{D}_z = \frac{e}{2}\sum_{i=1}^{A}\left(1+\tau_i^z\right)z_i \tag{4}$$

is the usual dipole operator projected in the z-direction.

The contribution due to exchange charge, $D^{(\mathrm{ex})}$, is typically at the order of $(v/c)^2$, and explicitly evaluated to be just a few percent of the polarization contribution for the deuteron case [10]; we therefore ignore it and approximate the full two-body contribution, $D^{(2)}$, solely by the polarization term

$$D^{(2)} = D^{(\mathrm{pol})} + D^{(\mathrm{ex})} \cong D^{(\mathrm{pol})}. \tag{5}$$

Our calculation of the EDM of ^{3}He therefore requires knowledge of both the individual EDMs of the nucleons and the $\not P \not T$ nuclear force. These very different quantities can only be related if some understanding exists of both the origin of the symmetry violation and its expression in strong-interaction observables. Constructing an effective field theory (EFT) that incorporates the symmetry violation, as well as the dynamics underlying the usual strong-interaction physics in nucleons and nuclei, provides a suitable framework. Chiral Perturbation Theory (χPT) supplemented with a knowledge of the symmetry violation would be the appropriate EFT. To date only a single such calculation exists [11], and it was applied to the one-nucleon sector, although further effort is underway [12,13]. The symmetry violation in that calculation was taken from the QCD $\bar{\theta}$ term, which leads to an isoscalar $\not P \not T$ pion–nucleon interaction in leading order, unlike the most general case that includes an isovector and an isotensor term, as well [14]. The non-analytic parts of the pion-loop diagrams [10,11,15,16] that generate nucleon EDMs then provide an appropriate estimate of the EDMs of individual nucleons. These contributions are expected to dominate in the chiral limit [15].

In the absence of a χPT calculation of $H_{\not P \not T}$ we revert to a conventional formulation in terms of a one-meson-exchange model. Including π-, ρ-, and ω-meson exchanges,[1] the interaction is given by (see Refs. [10,17–20]):

$$\begin{aligned} H_{\not P \not T}(\boldsymbol{r}) = \frac{1}{2m_N}\Big\{ & \boldsymbol{\sigma}_- \cdot \nabla\big(-\bar{G}^0_\omega y_\omega(r)\big) \\ & + \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2 \boldsymbol{\sigma}_- \cdot \nabla\big(\bar{G}^0_\pi y_\pi(r) - \bar{G}^0_\rho y_\rho(r)\big) \\ & + \frac{\tau^z_+}{2}\boldsymbol{\sigma}_- \cdot \nabla\big(\bar{G}^1_\pi y_\pi(r) - \bar{G}^1_\rho y_\rho(r) - \bar{G}^1_\omega y_\omega(r)\big) \\ & + \frac{\tau^z_-}{2}\boldsymbol{\sigma}_+ \cdot \nabla\big(\bar{G}^1_\pi y_\pi(r) + \bar{G}^1_\rho y_\rho(r) - \bar{G}^1_\omega y_\omega(r)\big) \\ & + \big(3\tau^z_1\tau^z_2 - \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\big)\boldsymbol{\sigma}_- \cdot \nabla\big(\bar{G}^2_\pi y_\pi(r) - \bar{G}^2_\rho y_\rho(r)\big)\Big\}, \end{aligned} \tag{6}$$

where m_N is the nucleon mass, $\bar{G}^T_x$ is defined as the product of a $\not P \not T$ x-meson–nucleon coupling $\bar{g}^T_x$ (with T referring to the isospin) and its associated strong one, $g_{x\mathrm{NN}}$ (e.g., $\bar{G}^0_\pi = g_{\pi\mathrm{NN}}\bar{g}^0_\pi$, where the interaction Lagrangian corresponding to these coupling constants is $\mathcal{L} = \bar{N}[ig_{\pi\mathrm{NN}}\gamma_5 + \bar{g}^0_\pi]\vec{\tau}\cdot\vec{\pi}N$), $y_x(r) = e^{-m_x r}/(4\pi r)$ is the Yukawa function with a range determined by the mass of the exchanged x-meson, $\vec{r} = \vec{r}_1 - \vec{r}_2$, $\vec{\sigma}_\pm = \vec{\sigma}_1 \pm \vec{\sigma}_2$, and similarly for $\vec{\tau}_\pm$. Unless the symmetry associated with the specific way that P-, T-violation is generated suppresses some of the couplings, one expects (by naturalness) that these $\not P \not T$ meson–nucleon couplings are of similar magnitude, and this is roughly confirmed by a QCD sum rule calculation [21].[2] We note, however, that in the (purely isoscalar) $\bar{\theta}$-term model of Ref. [11] the coupling constants $\bar{G}^1_\pi$ and $\bar{G}^2_\pi$ vanish, and the coupling constants for the short-range operators are very small compared to the pion one [13].

Because $H_{\not P \not T}$ violates parity and ^{3}He is (largely) an S-wave nucleus, the matrix elements that define the EDM (see below) mostly involve S- to P-wave transitions. This has the combined effect of suppressing the short-range contributions and enhancing the long-range (i.e., pion) contribution, irrespective of the detailed nature of the force. Combined with the consideration that the short-range parameters ($\bar{G}_{\rho,\omega}$) are not much larger than the pion ones, one can roughly expect the dominance of pion exchange.

3. ^{3}He in the ab initio no-core shell model

We solve the three-body problem in an ab initio no-core shell model (NCSM) framework [7]. The ground-state wave function is obtained by a direct diagonalization of an effective Hamiltonian in a truncated harmonic oscillator (HO) basis constructed in relative coordinates, as described in Ref. [22]. High-precision NN interactions, such as the local Argonne v_{18} [23] and the non-local charge-dependent (CD) Bonn potential [24] interactions, are used to derive an effective interaction in each model space via a unitary transformation [25] in a two-body cluster approximation. The Coulomb interaction between protons is also taken into account. Isospin violation is treated in the usual way [22] by modifying the NN interactions felt by each nucleon; this approach is valid to first order in isospin violation but ignores tiny components of the wave function with $T = 3/2$.

In addition to the phenomenological NN interaction models cited above, we consider two- and three-body interactions derived from EFT. In a recent work [26] using the NCSM, the presently available NN potential at N^{3}LO [27] and the three-nucleon (NNN) interaction at N^{2}LO [28,29] have been applied to the calculation of various properties of s- and p-shell nuclei. In that study a preferred choice of the two NNN low-energy constants, c_D and c_E, was found (and the fundamental importance of the chiral EFT NNN interaction was demonstrated) by reproducing the structure of mid-p-shell nuclei. (Note that these interactions are fitted only for a momentum cutoff of 500 MeV, and therefore we are not able at this time to demonstrate a running of the observables with the cutoff.) This Hamiltonian was then used to calculate microscopically the photo-absorption cross section of ^{4}He [30], while the full technical details on the local chiral EFT NNN interaction that was used were given in Ref. [31]. We use an identical Hamiltonian in the present work, and we compare its predictions against the phenomenological potentials.

In the NCSM the basis states are constructed using HO wave functions. Hence, all the calculations involve two parameters: the HO frequency Ω and $N_{\max}$, the number of oscillator quanta included in the calculation. At large enough $N_{\max}$, the results become independent of the frequency, although the rate of conver-

[1] Other mechanisms not included here are η-exchange and two-π-exchange, etc.

[2] In Ref. [21], $\bar{g}_{\rho,\omega}$ are defined differently; for conversion, see Ref. [10].