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Nuclear electric dipole moment of ^{3}He

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Abstract. In the no-core shell model (NCSM) framework, we calculate the ^{3}He electric dipole moment (EDM) generated by parity- and time-reversal violation in the nucleon-nucleon interaction. While the results are somehow sensitive to the interaction model chosen for the strong two- and three-body interactions, we demonstrate the pion-exchange dominance to the EDM of ^{3}He, if the coupling constants for π, ρ and ω-exchanges are of comparable magnitude, as expected. Finally, our results suggest that a measurement of ^{3}He EDM would be complementary to the currently planned neutron and deuteron experiments, and would constitute a powerful constraint to the models of the pion P- and T-violating interactions.

Keywords: electric dipole moment, parity and time-reversal violation, nucleon-nucleon interactions
PACS: 11.30Er, 21.10Ky, 21.60De, 21.60Cs

INTRODUCTION

Parity (P) non-conservation is well documented experimentally in nuclear processes. On the other hand, direct evidence of the breaking of time-reversal invariance has never been observed, and it's well suppressed in the Standard Model (SM). Permanent electric dipole moments (EDMs) are perfect candidates for an experimental determination of the time-reversal violation. Thus, since EDMs are a direct consequence of both parity and time-reversal violation, the measurement of such quantities would be the signal of physics beyond the standard model. Experimental programs are currently pushing the limits of EDMs in both neutron and deuteron. A new experimental scheme [1, 2, 3, 4, 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]. Here we examine the nuclear structure issues determining the EDM of ^{3}He and calculate the matrix elements of the relevant operators. We investigate what additional information an experiment on ^{3}He would bring and find that the measurements of neutron, deuteron and ^{3}He EDMs would put stringent limits on the theoretical models of the pion P- and T-violating interactions.

THEORETICAL OVERVIEW

In this investigation, we have considered two sources to the EDM: a one-body contribution induced by the intrinsic EDMs of the protons and neutrons, and the two-body contribution induced by the polarization effects produced by the P-, T-violating ($\not{P}$, $\not{T}$)

nucleon-nucleon (NN) interaction $H_{\not{P}\not{T}}$ (note that we neglect the $\not{P}\not{T}$ exchange charge resulting from $H_{\not{P}\not{T}}$, expected to be of the order of v^2/c^2).

The one-body contribution to the EDM of ^{3}He is calculated as an expectation value over the ground-state wave function $|0\rangle$ of maximal magnetic quantum number obtained through the diagonalization of the P, T-conserving interaction:

$$D^{(1)} = \langle 0| \sum_{i=1}^{A} \frac{1}{2} \left[(d_p + d_n) + (d_p - d_n)\,\tau_z(i)\right] \sigma_z(i) |0\rangle \,. \tag{1}$$

The two-body contribution is a direct consequence of the parity admixture in the ground-state wave function induced by $H_{\not{P}\not{T}}$. Using second order perturbation theory, the polarization contribution to the EDM is

$$D^{(2)} = \sum_n \frac{\langle 0|D_z|n\rangle\langle n|H_{\not{P}\not{T}}|0\rangle}{E_0 - E_n} + \text{c.c.}\,, \tag{2}$$

where $|n\rangle$ are excited states of negative parity obtained from the diagonalization of the P-, T-conserving interaction, and D_z is the usual dipole operator in the z direction.

We obtain the solution to the three-body problem in a no-core shell model (NCSM) framework [6, 7]. In this approach, an effective interaction is derived from high precission P-, T-conserving NN and three-nucleon (NNN) forces, by means of a unitary transformation. The ground-state wave function is expressed as a superposition of harmonic oscillator (HO) states in relative coordinates, and is obtained via a direct diagonalization of the effective interaction. Note that in the application to the observable considered in this investigation it is necessary to obtain with high accuracy excited states of the nucleus in the continuum, as implied by Eq. (2). This is an extremely difficult task in a NCSM framework, where the basis states are constructed using bound-state wave functions. We avoid calculating the continuum states by using Podolsky's method [8]. In this approach, the implementation of the second-order perturbation theory reduces to solving a Schrödinger equation with an inhomogeneous term. Thus, while the continuum states are never computed explicitly, they are implicitly included. A detailed description of the implementation in the NCSM formalism is presented in Ref. [9].

Aside from a method for solving the three-body problem, the main theoretical ingredients are the P-, T-conserving NN (and NNN) interactions, P-, T-violating NN interactions and intrinsic dipole moments of the nucleons. In principle, chiral perturbation theory (χPT) could constitute the appropriate theoretical framework in which all the observables could be treated consistently. Unfortunately, such a comprehensive approach is still under construction, especially for the P-, T-violating sector. Therefore, we are forced to decouple the problems as follows. In the P-, T-conserving sector we use phenomenological potential models such as the local Argonne V_{18} [10, 11], the non-local charge-dependent Bonn potential [12], as well as two-[13] and three-body [14, 15] interactions derived via χPT. The latter have been succesfully applied to the calculation of various properties of s- and p-shell nuclei in the same NCSM [16] framework. In the P-, T-violating sector we consider a one-meson-exchange formulation [17, 18, 19, 20, 21] for $H_{\not{P}\not{T}}$, in which the different terms come with unknown coupling strengths $\bar{G}_x^T$, where T refers in this case to the isospin channel, and x stands for the π, ρ or ω meson. We note that because ^{3}He is mainly a S-state nucleus, and $H_{\not{P}\not{T}}$ involves S- to P-wave transitions, the effect is two fold: (i) the long range contribution, i.e., pion, is enhanced, and (ii) the short-range contribution (rho and omega exchanges) are suppressed. Hence, if the $\not{P}$, $\not{T}$ coupling constants $\bar{G}_x^T$ are of similar magnitude as expected, the pion contribution dominates. Finally, the intrinsic EDMs of the nucleons are estimated from the non-analytic parts of the pion-loop diagrams [22, 23, 24], which are expected to dominate in the chiral limit.

RESULTS

We have calculated the ground-state wave function of ^{3}He using the phenomenological (P-, T-conserving) Argonne V_{18} and CD Bonn NN potentials; we have also used two- and three-body interactions derived from χPT, which reproduce with great accuracy the two-body observables and three-body binding energies. Note that in the case we use only two-body forces, the experimental binding energy of the three-body solution is not accurately reproduced, but an excellent agreement is obtained when both chiral NN and NNN interactions are used. The ground-state wave function is used further to calculate the EDM of ^{3}He as described in detail in Ref. [9].

A consistent approach would require that the same transformation used to derive the effective interaction be used for any observable calculated with the respective wave function. In this case, this means that the dipole moment operator and $H_{\not{P}\not{T}}$ in Eq. (2) should be also renormalized. However, previous investigations have shown that the long-range operators, like the dipole transition operator, are insensitive to the renormalization [25]. The long-range correlations are built by increasing the model space, in this case by increasing the number of HO shells used to construct the many-body basis. Hence, we observe the convergence of the EDM with the model space, and thus we find that in large size model spaces, the results become independent of the parameters used (HO frequency and number of HO shells).

Complete results for the π, ρ and ω exchanges have been reported in Ref. [9]. In Fig. 1, we present the convergence of the isoscalar, isovector and isotensor components of the EDM for the pion exchange. In the case presented here, the ground-state wave function was obtained by the diagonalization of the effective interaction obtained from the non-local CD Bonn NN interaction, while three-body forces were neglected. In the absence of an effective theory, which would achieve consistent description of P-, T-conserving and P-, T-violating observables, the model dependence cannot be completely removed from our results. However, the model dependence for the pion exchange is small, since the long-range part of the wave function shows little model dependence. Not surprisingly, the short-range contributions to the EDM, i.e., rho- and omega-meson exchanges, present a fairly strong dependence on the choice of the P-, T-conserving NN potential model. Nevertheless, because of the suppression of the short-range observables mentioned earlier, the magnitude of the ρ and ω contributions to the ^{3}He EDM are only about 10% of the pion exchange. In the hypothesis that the unknown P-, T-violating coupling constants $\bar{G}_x^T$ are of the same order of magnitude for π, ρ and ω exchanges, we thus conclude that the pion contribution dominates the EDM, and its value is

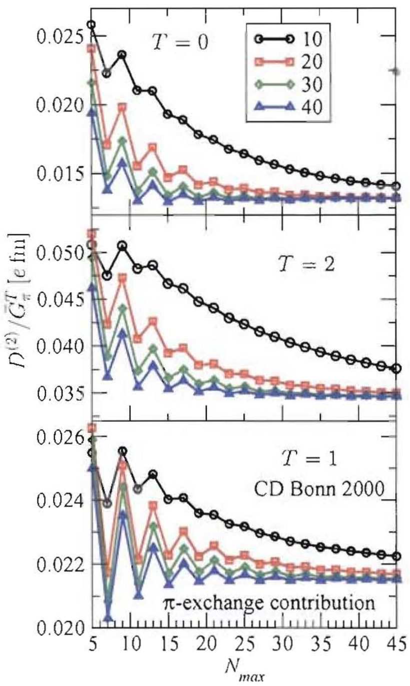

FIGURE 1. The EDM of ^{3}He, decomposed into isoscalar, isovector and isotensor contributions. These results have been obtained using the CD Bonn NN interaction.

$$D = D^{(1)} + D^{(2)} = (0.024\,G_\pi^0 + 0.023\,G_\pi^1 + 0.027\,G_\pi^2)\,e\,\mathrm{fm}. \tag{3}$$

This value was obtained after a compilation of all the potential models we have used (see Ref. [9]). (Note that in the absence of isospin violation in the Hamiltonian, as a consequence of the Wigner-Eckard theorem in the isospin space, there is a trivial relationship between the EDM of ^{3}He and that of the triton, i.e., the isoscalar and isotensor contributions change sign; the small isospin violation slightly breaks this symmetry.) If we compare this result with the neutron dipole moment $d_n = (0.010\,G_\pi^0 - 0.010\,G_\pi^2)\,e$ fm, and deuteron EDM, $d_{deut} = 0.015\,G_\pi^1\,e$ fm, we see immediately that the three EDMs are complementary. Thus, we can conclude that a measurement of these three systems would provide a valuable constraint for the theoretical models of P-, T-violating NN interactions.

SUMMARY

We have investigated the EDM of ^{3}He arising from the intrinsic dipole moments of the nucleons and the P-, T-violating NN interaction. We have used several potential models for NN (and NNN) interactions, finding a dominance of the pion-exchange contribution. Moreover, we have shown that a measurement of the ^{3}He EDM, in addition to the planned neutron and deuteron EDMs, can provide powerful experimental constraints on the theoretical models of the P-, T-violating interactions.

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