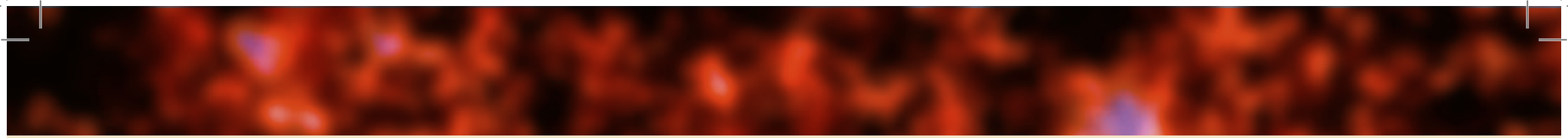

The Deuteron Electric Dipole Moment

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Direct measurement of the electric dipole moment of the neutron lies in the future—measurement of a nuclear electric dipole moment may well come first. The deuteron is one nucleus for which exact model calculations are feasible. We have investigated the model dependence of deuteron electric dipole moment calculations. One pion exchange dominates the electric dipole moment calculation, and separable potential model calculations will provide an adequate description of the deuteron electric dipole moment until such time as a measurement with a better than 10% accuracy is achieved.

With the discovery of nuclear parity (P) violation by Wu et al. [1], which had been suggested by Lee and Yang [2], it became clear that nucleons and nuclei could exhibit a nonzero electric dipole moment (EDM). Similarly, time reversal (T) violation could lead to a nonzero EDM. If the charge, parity, time (CPT) theorem is valid, then charge conjugation and parity (CP) violation would also imply an EDM. That a permanent electric dipole moment violates P and T can be seen from Fig. 1. If a system has a magnetic dipole moment ($\vec{\mu}$) and an electric dipole moment ($\vec{d}$), then under a parity transformation the electric dipole reverses its direction, whereas the magnetic dipole does not; under a time reversal transformation the electric dipole does not reverse its direction, whereas the magnetic dipole does. Whereas u is preserved under a P or T transformation, $\vec{d}$ is not; thus, the existence of an EDM violates P or T. Predating the discovery of parity violation in the weak interaction [1,2], Purcell and Ramsey worked with their student Smith to set limits on the neutron EDM [3]. The Standard Model of fundamental interactions predicts nonzero values for EDMs that are significantly smaller than contemporary experiments can detect. Therefore, an unambiguous observation of a nonzero EDM at current capabilities would imply a yet-to-be-discovered source of CP violation [4,5].

Current limits on the nucleon EDM are of the order of $10^{-26} e\ cm$. Even if one were to establish a nonzero neutron and proton EDM, the two results would at best determine only two of the three isospin (isoscalar, isovector, and isotensor) components. One would need a third measurement, such as the deuteron EDM, or the triton or ^{3}He EDM, to fully elucidate the isospin nature of the EDM operator. The deuteron is attractive as the focus of an EDM investigation, experimental and theoretical, because a method to directly measure the EDM of charged ions in a storage ring has been proposed [6-9]. A permanent ^{2}H EDM can arise, because a PT violating one-pion-exchange interaction can induce a small P-state admixture in the deuteron wave function, which produces a non-vanishing matrix element of the charge dipole operator $\tau^2\_\vec{er}$. Although this two-body EDM contribution must be combined with the one-body contributions of the neutron and proton, the neutron and proton EDMs tend to cancel in the case of the isospin zero ^{2}H. Therefore, the PT violating nucleon-nucleon (NN) interaction can contribute significantly to the deuteron EDM. Because the deuteron is reasonably understood and has been accurately modeled, reliable calculations are possible. We have addressed the sensitivity of the deuteron EDM to the nuclear physics in the modeling of the NN interaction. We have examined the uncertainties in the deuteron EDM calculation arising from the short-range repulsion in the ground state wave function, from the dependence on the size of the deuteron D-state, and from the properties of the $^3P_1$ continuum in the intermediate states.

The total one-body contribution $d^{(1)}{}_D$ to the deuteron EDM due to the neutron and proton is the sum $d^{(1)}{}_D = d_n + d_p$, whereas the total deuteron EDM is the sum of the one-body term and the two-body contribution $d^{(2)}{}_D$, $d_D = d^{(1)}{}_D + d^{(2)}{}_D$. Our focus is on $d^{(2)}{}_D$. Liu and Timmermans [10] calculated this term using three contemporary realistic potential models

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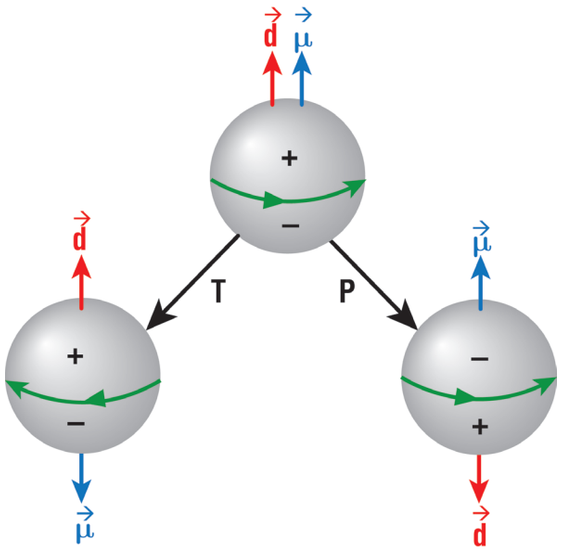

Fig. 1. Electric dipole moment leading to parity (P) and time reversal (T) violation.

within the range of uncertainty (< 2%), $d^{(2)}{}_{D} \approx$ -0.73 ± 0.01 *Ae* fm, where $A = \bar{g}^{(1)}_{\pi NN} g_{\pi NN}/(16\pi)$ and *e* is the electric charge. Our analysis is based upon a separable potential formulation of the Hamiltonian and a writing of the EDM as a sum of two terms: the first depends on the target wave function with plane-wave intermediate states (d_{PW}), and the second depends on intermediate multiple scattering in the $^3P_1$ channel (d_{MS}). We concluded the following five points: (1) In the absence of multiple scattering, the variation in $d^{(2)}{}_{D} = d_{PW}$ due to differences in the deuteron wave function is less than 5%. (2) The contribution from multiple scattering, d_{MS}, is sensitive to the short range behavior of the ^2H wave function, and the d_{MS} contribution is about 20% for realistic parameterizations of the deuteron. This suggests that we may extend the analysis to heavier nuclei in the plane wave approximation with an estimated error of some 20%. (3) The contribution from the $^3P_1$ interaction via d_{MS} depends on the phase shifts in this channel as well as the off-shell properties of the amplitude; however, contemporary phase shifts suggest that the d_{MS} term is much smaller than d_{PW}. (4) As suggested by Liu and Timmermans, one-pion exchange dominates the deuteron EDM calculation. (5) A comparison of our results with those of Liu and Timmermans indicates that one may use a separable potential approximation in, for example, ^3H and ^3He calculations with minimal loss of accuracy. Moreover, until an accuracy of better than 10% is achieved in ^2H EDM measurements, separable potential model calculations should provide an adequate description.

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