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A LIMIT ON NUCLEAR T-VIOLATION FROM THE NEUTRON ELECTRIC DIPOLE MOMENT[†]

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ABSTRACT

Time reversal non-invariance in nuclei has recently been parametrized in terms of a four point coupling, of undetermined strength, of an isovector photon, a charged pion and the nucleon current. If parity violation is introduced via the weak interaction, this coupling is restricted, by the failure to observe a neutron electric dipole moment, to a size which is an order of magnitude smaller than the limit imposed by present nuclear γ-decay experiments.

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In a recent letter[1] Clement and Heller discuss the expected size of T-violating effects in nuclear γ-decay arising from a possible C and T non-invariance of the electromagnetic interaction.[2] We investigate here the limit imposed on these effects by the failure to observe a neutron electric dipole moment.[3]

Clement and Heller calculate the T-odd two nucleon matrix elements of the long range E1 and M1 multipole operators from a supposed T-violation in the four point coupling of an isovector photon, a charged pion and the nucleon current. They make a 'rough guess' as to that size of coupling constant which would correspond to a large or 'maximal' effect and conclude that the most sensitive present limit on the E2-M1 phase (in ^{36}Cl) still falls short of probing such an effect. The virtue of this approach is that it avoids the consideration of off-shell nucleons that necessarily attends any attempt to parametrize T-violation without P-violation at the NNγ vertex.[4]

The question arises whether the coupling they take as 'maximal' would lead to observable effects in other low energy T-violation tests. More usefully, we would like to know whether the present nuclear experiments, when interpreted in their model, are more or less sensitive to electromagnetic T-violation than is the present experimental upper limit[3] of 5×10^{-23} cm on the neutron electric dipole moment (EDM). Our calculation indicates that they are an order of magnitude less sensitive.

Consider the following conventional, P-violating, and T-violating Lagrangians:

$$\mathscr{L} = ig\, \overline{\Psi}\, \vec{\tau} \cdot \vec{\phi}\, \gamma^5 \Psi\, , \qquad (1)$$

$$\mathscr{L}_1 = g_1 \overline{\Psi}\, (\vec{\tau} \times \vec{\phi})_3\, \Psi\, , \qquad (2)$$

$$\mathscr{L}_2 = ig_2 (e/m\mu)\, \overline{\Psi} (\vec{\tau} \times \vec{\phi})_3\, \gamma^5 \sigma^{\mu\nu} \Psi\, F_{\mu\nu}\, , \qquad (3)$$

where g is the strong coupling constant, m and μ are the nucleon and pion masses and our gamma matrices are as in Ref. 1. Parity violation in the low energy pion-nucleon interaction necessarily involves charged pions[5] and s-wave non-leptonic hyperon decay rates, PCAC and current algebra[6,7] fix $\sqrt{2}|g_1| = 4 \times 10^{-8}$. Note that g_1 is small since it depends on the Cabbibo angle through a factor $\sin^2\theta$. The T-violating interaction $\mathscr{L}_2$ is that used by Clement and Heller, who choose $g_2 = \pm 1$ as representing a 'maximal' violation and calculate γ-decay effects arising from Fig. 1a. If in addition we allow the possibility of P-violation through $\mathscr{L}_1$, a nucleon EDM will result from Fig. 1b just as a nucleon anomalous magnetic moment results from Figs. 1c and d.

We calculate the neutron EDM from a sideways dispersion relation,[8] assumed valid without subtraction and threshold dominated by low energy πN intermediate states. The treatment closely parallels Drell and Pagels' calculation of the nucleon magnetic moments.[9] Barton and White[7] introduced the dispersion relation as providing a theoretically defensible lower limit on the EDM, given a mechanism of T-violation, and in a previous paper[10] we calculated the effect of T-violation at $N^*N\gamma$ vertices. Details of the calculation and further references may be found in Refs. 7-10.

The electromagnetic form factors of the nucleon, at $k^2 = 0$, satisfy dispersion relations in the nucleon mass.[8] The anomalous magnetic moments $\mu_M^{p,n} = e\kappa^{p,n}/2m$ and electric dipole moments $\mu_E^{p,n} = e\beta^{p,n}$ may be simply calculated if we include only the contribution of πN intermediate states to the absorptive parts. These are then given by the $NN\pi$ coupling, with one nucleon off-shell, and <u>physical</u> photoproduction amplitudes (Fig. 2). As a further approximation we neglect rescattering corrections in the intermediate state. The off-shell $NN\pi$ P-conserving and P-violating couplings are then simply given by g and g_1 and photoproduction amplitudes must be real, unless there is T-violation. We describe pion photoproduction by the CGLN invariant amplitudes.[11] Actually it is only necessary to consider the contribution of the amplitudes $A^{(\pm,o)}$ to reconstruct the Drell and Pagels result and to calculate the EDM. We find

$$\begin{bmatrix} \mu_M^{p,n} \\ \\ \mu_E^{p,n} \end{bmatrix} = \frac{1}{\pi} \int_{(m+\mu)^2}^{\infty} \frac{dW^2}{(W^2-m^2)} \, \frac{m|\vec{q}|}{8\pi W(W^2-m^2)} \int_{-1}^{+1} d(\cos\theta) \begin{bmatrix} g(p_1k-p_2k)\mathrm{Re}(3A^{(o)} \pm (2A^{(-)}+A^{(+)})) \\ \\ g_1(p_1k+p_2k)\mathrm{Im}(2A^{(-)} \pm 2A^{(o)}) \end{bmatrix}, \tag{4}$$

where W, θ and $\vec{q}$ are the c.m. energy, scattering angle and pion momentum and the ± signs refer to proton and neutron.

Drell and Pagels calculated μ_M from near threshold πN contributions, approximated by the electric Born terms, which give the low energy theorem in the limit of massless pions.[12] The charge couplings contribute to the CGLN amplitudes A and B only, and B does not contribute to the magnetic moments. We recover their result from Eq. (4) by taking the electric Born approximation to $A^{(\pm,o)}$, ignoring terms in (μ/m) and cutting off the dispersion integral at $W = \lambda m$, with $\lambda \approx 1.5$. This gives[9] 70% and 90% of the proton and neutron experimental values. The moderate success of this calculation results from taking only the near threshold contribution, which is predominantly isovector. Letting $\lambda \to \infty$ merely gives the unsatisfactory perturbation theory result of Figs. 1c and d, namely $\kappa^p = -\kappa^n/4 = g^2/16\pi^2$.

Our calculation of μ_E capitalizes on the success of this threshold calculation. Equation (2) gives $\mathrm{Im}A^{(-)} = -2eg_2/m\mu$. Again we neglect terms in (μ/m) and introduce the cut-off λ, to obtain from Eq. (4)

$$\beta^p = \beta^n = -\frac{1}{\mu} \left(\frac{g_1 g_2}{8\pi^2}\right) \left(3\ln\lambda^2 + 1 - \frac{1}{\lambda^2}\right). \tag{5}$$

The result diverges as $\lambda \to \infty$, as would be expected from a power count in Fig. 1b. This is not unduely worrying since the validity of our approach rests on the assumption of threshold dominance, given that Eq. (2) adequately represents low energy effects. With $\lambda = 1.5$ we obtain $|g_2| < 0.3$, to be compared with Clement and Heller's 'maximal' assumption, $|g_2| = 1$, which leads in their model to nuclear γ-decay effects smaller than could so far be detected,[1] by a factor of at least 3. Detailed investigation[13] of the magnetic moment dispersion relation, utilizing experimental πN phase shifts and photoproduction multipoles and including η N intermediate states, indicates that the result of our naïf calculation may be believed to with a factor of say 2.

We conclude that, if $\mathscr{L}_2$ adequately represents a low energy electromagnetic T-violation in the πN system, then the limit on the EDM is an order of magnitude more sensitive to the effect than is the best nuclear measurement.

This situation is to be contrasted with our previous findings,[10] namely that the EDM restricts T-violation at the $\Delta N\gamma$ vertex less than do present reciprocity measurements[14] and the limit on an up-down asymmetry in polarized inelastic electron scattering.[15]

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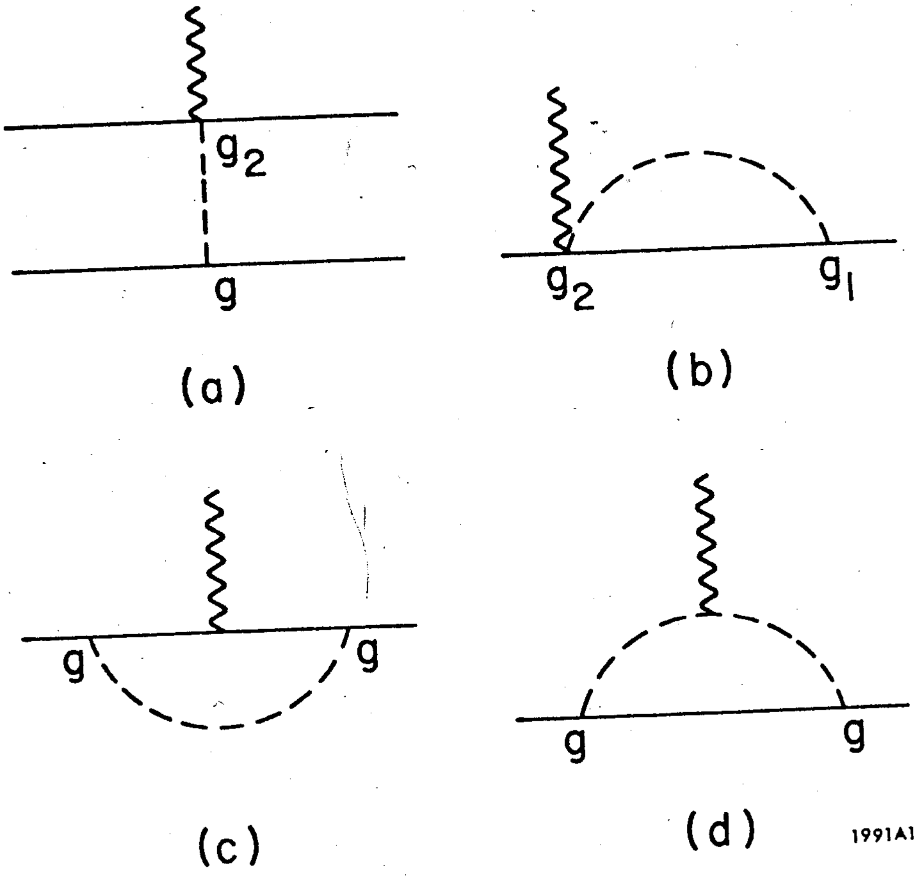
FIGURE CAPTIONS

1. (a) T-violation in the two nucleon electromagnetic operator,

   (b) Contribution to EDM from combined T- and P-violation,

   (c) and (d) Conventional contributions to the nucleon anomalous magnetic moments.

2. The πN contributions to the absorptive parts of nucleon form factors, as a function of W, where $p^2 = W^2$ and all other particles are on-shell.



(a) (b)

(c) (d)

Fig. 1

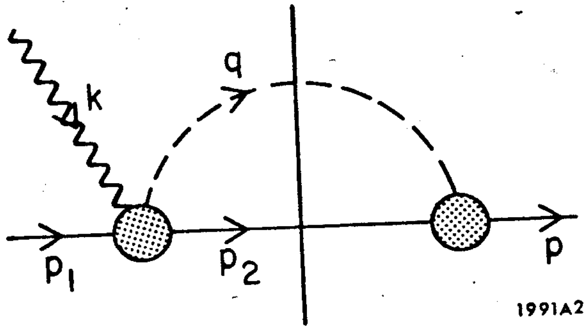


Fig. 2