Electric dipole moment of the neutron according to Weinberg's *CP*-violating model

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According to Weinberg's *CP*-violating model, the electric dipole moment of the neutron is determined by an interaction with neutral Higgs bosons and is two or three orders of magnitude greater than the upper limit which has already been established experimentally.

All estimates of the electric dipole moment of the neutron which have been based on Weinberg's *CP*-violating model[1–5] fall in a rather narrow interval, 10^{-24}–10^{-25} electron · cm, which is near the existing experimental upper limit,[6] $|D_n| < 3.6\times 10^{-25}$ electron · cm. The interaction of quarks with neutral Higgs bosons has been ignored here since it has been assumed that this interaction is proportional to the cube of the mass of the light quarks.[7] In the present letter we show that a correct estimate of the constant for the coupling of the nucleon with a neutral Higgs boson at low momenta leads to an electric dipole moment which is proportional to the mass of the nucleon and which does not vanish in the chiral limit.

The Lagrangians for the interaction of scalar (σ) and pseudoscalar (H) Higgs bosons with a quark q are

$$\mathcal{L}_\sigma = -\frac{m_q}{v_q}(\bar{q}q)\sigma\,, \qquad \mathcal{L}_H = -\frac{m_q}{v_q}(\bar{q}\,i\gamma_5 q)H\,, \tag{1}$$

where m_q is the quark mass, and v_q is the vacuum expectation value which leads to the mass m_q. Using the results of Ref. 8 to calculate the scalar matrix element

$\langle N | m_q \bar{q} q | N \rangle$, and ignoring the small ($\sim 10\%$) contribution from the "light" u and d quarks, we find the following expression for the Lagrangian of the interaction of the nucleon with σ:

$$\mathcal{L}_{\sigma N} = -\frac{2}{29} m_N \Big(\sum_h \frac{1}{v_h} \Big) (\bar{\psi}_N \psi_N) \sigma . \tag{2}$$

Here the summation is over the heavy quarks only, and m_N is the mass of a nucleon. It is easy to show that the coupling of a pseudoscalar boson with a nucleon is determined by equations similar to those[9] that determine the coupling of an axion with a nucleon:

$$\begin{aligned} \mathcal{L}_{HN} &= [\, \bar{\psi}_N (g_H^0 + g_H^1 \tau_3) i \gamma_5 \psi_N \,] H , \\ g_H^0 &= (-g_A^0) \frac{m_N}{2} \sum_h \frac{1}{v_h} , \\ g_H^1 &= (-g_A) \frac{m_N}{m_u + m_d} \left[\frac{m_d}{v_d} - \frac{m_u}{v_u} - \frac{m_u}{2} \sum_h \frac{1}{v_h} \right] . \end{aligned} \tag{3}$$

We take the isoscalar and isovector axial form factors of the nucleon, g_A^0 and g_A, to be equal ($g_A^0 \simeq g_A = -1.25$). To estimate the electric dipole moment of the nucleon, we carry out calculations for the simplest diagram (Fig. 1), where the vertex representing the interaction of the γ ray with the nucleon is $e\gamma_\mu - \mu_N' \sigma_{\mu\nu} q_\nu$ if we ignore departure from the mass shell (μ_N' is the anomalous magnetic moment of the nucleon). We then find

$$D_N = \mu_N \int_0^\infty \frac{d^4 k}{i (2\pi)^4} (2kp) \frac{g_\sigma F_\sigma(k^2) g_H F_H(k^2)}{\left[m_N^2 - \left(k - \frac{p}{2} \right)^2 \right]^2} < \sigma H >_k . \tag{4}$$

Here g_σ and g_H are the scalar and pseudoscalar coupling constants, defined by (2) and (3); $\langle \sigma H \rangle_k$ is the propagator corresponding to the mixing of the σ and H bosons; $p = p_1 + p_2$; and $\mu_N = e/2m_N + \mu_N^1$. The scalar form factor $F_\sigma(k^2)$ will presumably

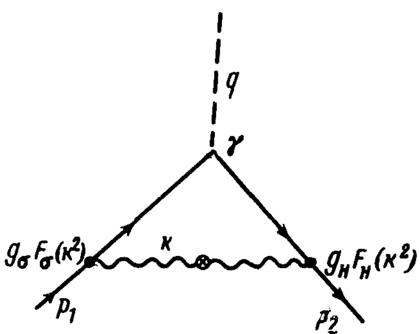

FIG. 1.

not suppress the contributions of momenta less than ~ 1 GeV. The pseudoscalar vertex is determined primarily by its isoscalar part, g_H^0, which is nonvanishing in the chiral limit. It arises because of the triangle anomaly and is naturally associated with a form factor determined by the pole of the η' meson. The contribution of the η meson disappears in the chiral limit, but numerically it is of the same order of magnitude as the η' contribution. Since $m_{\eta'} \simeq m_N$, we assume, for simplicity,

$$F_H(k^2) \simeq F_\sigma(k^2) \simeq \frac{m_N^2}{k^2 + m_N^2}. \tag{5}$$

The form factor associated with the isovector part of g_H^1 is determined by a π-meson pole and contains a suppression factor $\sim (m_\pi/m_N)^2$. If we accordingly ignore the contribution from g_H^1 and assume that the mass of the Higgs particles is much greater than m_N, we can take the propagator $\langle \sigma H \rangle$ through the integral sign in (4) at the point $k \simeq 0$. Assuming, for simplicity, that all the vacuum expectation values are the same, $v = (G_F\sqrt{2})^{1/2} = 250$ GeV, we find from (2)–(5)

$$D_n = 2.3 \times 10^{-3} \mu_n \frac{<\sigma H>_0}{v^2} m_N^2, \qquad D_p = - D_n \frac{\mu_p}{\mu_n} . \tag{6}$$

Although the quantity $\langle \sigma H \rangle_0 / v^2$ is not known experimentally, there is absolutely no reason to believe that it is substantially different from the corresponding value of ImA (0) for charged Higgs bosons. (See Ref. 7 for proof that $\langle \sigma H \rangle \neq 0$ if Im$A \neq 0$.) Substituting into (6) the value of ImA (0) found in Ref. 2 from experiments with K mesons, we find

$$D_n \simeq 10^{-22} \text{ electron} \cdot \text{cm}. \tag{7}$$

We thus see that the axial anomaly and the anomaly in the trace of the energy-momentum tensor account for the strong coupling of neutral Higgs bosons with nucleons. As a result, their contribution to the electric dipole moment of the neutron does not vanish in the chiral limit and is much greater than the contribution from charged particles. The resulting electric dipole moment turns out to be two or three orders of magnitude higher than the present experimental upper limit. At present, there is reason to believe[10] that ImA (0) may be, say, an order of magnitude smaller than the value assumed here. If it is, there would be a proportionate decrease in all the estimates in Weinberg's model. In principle, we cannot rule out the possibility that the mixing of neutral bosons is substantially less pronounced than that of charged bosons, but the value found for D_n still appears to be a serious argument against Weinberg's CP-violating model.

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