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Some Consequences of the Proposed C and T Violations in Electromagnetic Interactions*

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The model in which C and T are violated in the electromagnetic interactions of hadrons is considered further. It is shown that in this model, the nucleons should have electric dipole moments of order 10^{-19} cm$\times e$, comparable to the present upper limit for the neutron electric dipole moment. The effect of mixing between η^0 and $X^0(960)$ on the decays $\eta^0 \to \pi^0 e^+ e^-$, $X^0 \to \pi^0 e^+ e^-$, and $X^0 \to \eta^0 e^+ e^-$ is discussed, and some estimates for the branching ratios are presented. It is found that the branching ratios of these to all η^0 and X^0 decays may be about 1%.

I. INTRODUCTION

RECENTLY[1] it has been proposed that the CP-violating decay[2] $K_2 \to 2\pi$ occurs through a combination of the CP-conserving weak interaction, and a P-conserving, CP-violating term in the electromagnetic interaction of the hadrons. In this paper, some consequences of this model are pointed out. These concern the electric dipole moments of the baryons, and some of the proposed direct tests of the C-violating electromagnetic interaction. The first of these points involves only the assumption that the source of the CP violation is electromagnetic. On the other hand, the analysis of electromagnetic decays of hadrons involves some assumptions about the $SU(3)$ transformation properties[3] of the $C=+1$ electromagnetic current K_μ. Some remarks are also made about ways to distinguish electromagnetic C violations from strong C violations.

II. ELECTRIC DIPOLE MOMENT OF BARYONS

The existence of an electric dipole moment (EDM) for the neutron or proton would be an indication of CP violation for some interaction. It has been pointed out[4] that such a dipole moment could be generated by a weak, CP-violating, $\Delta S=0$, four-baryon interaction. In the presence of such an interaction, one would expect the EDM of a nucleon to be approximately

$$d \simeq eG_F m_p \sin\theta \simeq (10^{-19} \sin\theta)\ \text{cm}\times e, \tag{1}$$

where $\sin\theta$ is a phase angle measuring the CP violation in weak interactions. In the absence of a detailed dynamical argument to the contrary, one considers the small magnitude of the ratio $(K_2 \to 2\pi)/K_1 \to 2\pi)$ as indicative of the size of $\sin\theta$. Then one would expect that if the CP violation is an intrinsically weak interaction

$$\sin\theta \lesssim 10^{-3},$$

and (2)

$$d \lesssim 10^{-22}\ \text{cm}\times e.$$

This conclusion is insensitive to the existence or nonexistence of intermediate bosons.

Suppose,[1] however, that a term K_μ, even under T, occurs in the electromagnetic current of the hadrons. Suppose further that the matrix elements of K_μ are comparable to these of the regular electromagnetic current J_μ. Then provided only that there are weak, P-violating, $\Delta S=0$, four-baryon interactions, as experiment seems to indicate,[5] one would expect the nucleon to get an EDM of order

$$d \simeq eG_F m_p \simeq 10^{-19}\ \text{cm}\times e, \tag{3}$$

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[1] J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. **139**, B1650 (1965).

[2] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters **13**, 138 (1964).

[3] T. D. Lee, Phys. Rev. (to be published); N. Cabibbo, Phys. Rev. Letters **14**, 965 (1965).

[4] G. Feinberg and H. S. Mani, Phys. Rev. **137**, B636 (1965).

[5] F. Boehm and E. Kankeleit, Phys. Rev. Letters **14**, 312 (1965).

or 10^3 times larger than in the other model. This EDM comes about through the matrix element

$$\langle N|H_{w,0}{}^{\Delta S=0}K_\mu|N\rangle\,, \qquad (4)$$

where $H_{w,0}{}^{\Delta S=0}$ is the odd parity part of the $\Delta S=0$, four-baryon interaction. The indicated magnitude of the EDM is comparable to the present upper limit[6] for the neutron EDM, so that a modest increase in the accuracy of such measurements would be a way of gaining information about K_μ. Other proposed models[7] of CP violation in K_2 decay generally predict EDM's smaller than Eq. (3) by several orders of magnitude, except for models in which the smallness of the ratio $(K_2\to 2\pi)/(K_1\to 2\pi)$ is an unexplained accident.

III. ELECTROMAGNETIC DECAYS OF MESONS

One way of testing for the existence of K_μ is to search for the decay

$$\eta^0\to\pi^0e^+e^-. \qquad (5)$$

We note that the existence of a ninth pseudoscalar meson X^0, with a mass of 960 MeV, is relevant to the possible occurrence of this decay. Since the X^0 has the same I and Y as the η^0, a mixing can take place between them, just as between the ϕ and ω vector mesons. This mixing can be estimated, as for the ϕ, ω system, by assuming that the deviation of the η^0 mass from the Gell-Mann–Okubo mass formula comes entirely from such mixing. It is found that the physical X^0 and η^0 can be written in terms of a bare unitary singlet X_1, and a member η_8 of a unitary octet by[8]

$$\begin{aligned}X^0&=X_1\cos\theta+\eta_8\sin\theta\,,\\ \eta^0&=-X_1\sin\theta+\eta_8\cos\theta\,,\end{aligned} \qquad (6)$$

with $\tan\theta=0.18$.

It has been shown[5] that if K_μ transforms as a member of an $SU(3)$ octet, then in the limit of exact $SU(3)$ symmetry of strong interactions, the matrix element

$$\langle\eta_0|K_\mu|\pi^0\rangle$$

vanishes. This occurs because η_8 and π^0 are members of the same unitary multiplet, and under the stated assumptions, the matrix element $\langle\eta_8|K_\mu|\pi^0\rangle$ can be related to the diagonal matrix element $\langle\eta^0|K_\mu|\eta^0\rangle$, which vanishes by Hermiticity.[1]

On the other hand, since X_1 is not in the same multiplet as η_8 and π^0, no condition on the matrix elements

$$\langle X_1|K_\mu|\pi^0\rangle \quad\text{or}\quad \langle X_1|K_\mu|\eta_8\rangle$$

follows from $SU(3)$. Hence assuming that $\langle\eta_8|K_\mu|\pi^0\rangle$ vanishes, we find for the physical matrix elements

$$\begin{aligned}\langle\eta^0|K_\mu|\pi^0\rangle&=-\sin\theta\langle X_1|K_\mu|\pi^0\rangle\,,\\ \langle X^0|K_\mu|\pi^0\rangle&=\cos\theta\langle X_1|K_\mu|\pi^0\rangle\,,\\ \langle X^0|K_\mu|\eta^0\rangle&=\langle X_1|K_\mu|\eta_8\rangle\,.\end{aligned} \qquad (7)$$

If we make the further assumption[3] that K_μ transforms under $SU(3)$ in the same way as the regular current J_μ, we find in addition that

$$\langle X_1|K_\mu|\pi^0\rangle=\sqrt{3}\langle X_1|K_\mu|\eta_8\rangle\,. \qquad (8)$$

In this case, the three decays

$$\begin{aligned}&\eta^0\to\pi^0e^+e^-\,,\\ &X^0\to\pi^0e^+e^-\,,\\ &X^0\to\eta^0e^+e^-\,,\end{aligned} \qquad (9)$$

are described by a single form factor, defined by

$$\begin{aligned}\langle X_1|K_\mu|\pi^0\rangle=&f_1(q^2)\\ &\times[(X_\mu+\pi_\mu)-((m_x^2-m_\pi^2)/q^2)(\pi_\mu-X_\mu)]\,,\end{aligned} \qquad (10)$$

in a notation similar to Ref. 1. The form factor $f_1(q^2)$ must vanish at $q^2=0$. If we assume that $q^{-2}f_1(q^2)$ is approximately constant over the decay spectra, we obtain ratios for the decays of Eq. (9) from Eqs. (7), (8), and Eqs. (34), (35) of Ref. 1.

$$\begin{aligned}&(R_\eta\to\pi^0e^+e^-)/(R_X\to\pi^0e^+e^-)\\ &\qquad\simeq\tan^2\theta\ (m_\eta/m_X)^5\tfrac{1}{2}\simeq 0.001\,, \qquad (11)\\ &(R_X\to\eta e^+e^-)/(R_X\to\pi^0e^+e^-)\\ &\qquad\simeq(3\cos^2\theta)^{-1}[(1-\epsilon^2)(1-8\epsilon+\epsilon^2)\\ &\qquad\qquad-12\epsilon^2\ln\epsilon]\simeq 0.03\,, \qquad (12)\end{aligned}$$

with $\epsilon=(m_\eta/m_X)^2\simeq\frac{1}{3}$. Thus in this model the decay $X^0\to\eta^0e^+e^-$ should be very small compared with $X\to\pi^0e^+e^-$.

The absolute decay rates for these modes depend on the size of f_1. We write

$$f_1=-\tfrac{1}{6}eq^2\langle r^2\rangle\,, \qquad (13)$$

and take $\langle r^2\rangle=\lambda\langle r^2\rangle_p$, where $\langle r^2\rangle_p$ is the mean-square proton-charge radius, and λ is a dimensionless parameter, which is of order 1 if there is a large electromagnetic C violation. Then

$$\begin{aligned}R_\eta&\to\pi^0e^+e^-\simeq 2.5\lambda^2\ \text{eV}\,,\\ R_X&\to\pi^0e^+e^-\simeq 2.5\lambda^2\ \text{keV}\,,\\ R_X&\to\eta e^+e^-\simeq 80\lambda^2\ \text{eV}\,.\end{aligned} \qquad (14)$$

These widths may be compared with estimates[8] of the total X and η widths:

$$\begin{aligned}(R_\eta&\to\text{anything})\approx 300\ \text{eV}\,,\\ (R_X&\to\text{anything})\approx 100\ \text{keV}\,.\end{aligned} \qquad (15)$$

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[6] J. H. Smith, E. M. Purcell, and N. F. Ramsey, Phys. Rev. **108**, 120 (1957).

[7] For example, T. D. Lee and L. Wolfenstein, Phys. Rev. **138**, B1490 (1965); F. Zachariasen and G. Zweig, Phys. Rev. Letters **14**, 794 (1965).

[8] R. H. Dalitz and D. G. Sutherland, Nuovo Cimento **37**, 1777 (1965).

Hence the branching ratios in each case might be about a percent for the pionic mode. In the case of $X^0 \to \pi^0 e^+ e^-$, the q^2 dependence of the form factor may not be negligible as assumed here.

There does not seem to be any similar mechanism to thwart the restriction of $SU(3)$ on T violation in $\Sigma^0 \to \Lambda^0 e^+ e^-$, unless the $Y_0^*(1405)$ is a $\frac{1}{2}^+$ particle which mixes with the Λ^0.

IV. GENERAL COMMENTS ON C VIOLATION

It is necessary to distinguish the model of a large C violation in electromagnetic interactions from models in which C is violated in strong interactions.[9] A large C violation in strong interactions might give values similar to Eq. (14) for electromagnetic decays. In our opinion, such a model is ruled out by the evidence for T conservation in nuclear reactions cited in Ref. 1. Because of this, it would appear that a C violation in strong interactions could at most be an effect of a few percent. Such an interaction can be distinguished from a large C violation in electromagnetism by the fact that the former gives much smaller C-violating effects in electromagnetic decays than the latter. That is, if the primary C violation is a few percent correction to strong interactions, and does not directly involve photons, then we would expect effects smaller than Eq. (14) by a factor of about 100 in the reactions cited.

It should also be noted that if the source of CP violation is electromagnetic, so that the $K_2 \to 2\pi$ decay proceeds via a weak and two electromagnetic interactions, one would expect that

$$R_{2\pi} = (K_2 \to 2\pi^0)/(K_2 \to \pi^+\pi^-) \neq \tfrac{1}{2}, \qquad (16)$$

as it is for the K_1. This conclusion does not depend on the isotopic transformation properties of the current K_μ. On the other hand, if the CP violation originates in an isotopic-spin–conserving strong interaction,[9] then we expect that the ratio $R_{2\pi}$ would be equal to $\frac{1}{2}$, provided that the intrinsic weak interaction satisfies the $\Delta I = \frac{1}{2}$ rule.

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[9] J. Prentki and M. Veltman, Phys. Letters **15**, 88 (1965); S. Glashow and C. Sommerfield, Phys. Rev. Letters **15**, 78 (1965).