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*MODELS FOR THE VIOLATION OF CP SYMMETRY**

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SINCE the violation of CP-invariance was observed in the decay of kaons, many articles have been written on the theoretical aspects of this problem. The overwhelming majority of these articles were of a purely phenomenological character, they discussed phenomena in which other aspects of CP-noninvariance could be observed. No real attempts have been made to explain the dynamical origin of CP-nonconservation. And if one leaves out from a discussion of models of CP-violation those like the assertion that the violation of CP-symmetry could be due to a violation of C-symmetry in strong interactions or to the presence of currents of the second kind, there remains very little. In essence, there remain only a few theories attributing to the intermediate vector boson, which is mediating the weak interactions, some definite properties, and the model proposed by T. D. Lee, which relates the violation of C-invariance in electromagnetic interactions with the existence of a new species of particles, called a-particles[1]. In his introductory remarks at the Berkeley Conference in 1966, Gell-Mann has jokingly introduced the assumption that there exist "chimerons," which are responsible for everything that is not understood in elementary particle physics. One could hardly assume that this joke has been taken seriously. Nevertheless, there appeared several papers which considered the assumption that the W-meson of weak interactions and the a-particle of T. D. Lee are identical. I would never have imagined that I would ever have to discuss such models, but lacking others, I have no choice.

The first paper devoted to C-violation due to the W-meson was written by F. and G. Salzman[2]. They attributed to the intermediate boson of the weak interactions an electric dipole moment. They introduced into the electromagnetic interaction lagrangian a term of the form

$$-{}^1/_2 ie\lambda\varepsilon_{\mu\nu\alpha\beta}F_{\alpha\beta}W^*_\mu W_\nu,$$

where, as usual,

$$F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha.$$

This term produces violations of P and T in electromagnetic interactions of the boson. This model, which is characterized by the presence of one free parameter, has several features in common with other theories of CP-violation in electromagnetic interactions.

It is hard to understand, from the viewpoint of such theories, why the electric dipole moment of the neutron is so small. More precisely, according to the estimate of the Salzmans, the parameter λ should be of the order of unity, in order to be able to obtain the experimentally observed rate of the two-pion decay of the K^0_L. However, using the same value of the parameter for computing the electric dipole moment of the neutron in a naive model, they have found (taking $m_W \sim 2m_N$)

$$\mu_E \approx 8\cdot 10^{-21}\ \text{cm}$$

to be compared with the presently available experimental limit[3] $(-2 \pm 3) \times 10^{-22}$ cm[1]. As already stressed by L. Okun' at the Heidelberg Confernce, this circumstance should be considered a serious blow to the theory of CP-violation in electromagnetic interactions, including the Salzman model. Compared to other models of electromagnetic C-violation the Salzman model has the advantage that it predicts the absence of any effects of C-violation in nonweak processes like the decays $\eta \to \pi\pi\gamma$ or $X \to \pi\pi\gamma$, where indeed such effects have not been observed. On the other hand the electric dipole moment of the intermediate boson is a rather artificial thing, which to the majority of theorists is not too attractive.

Next we consider the very clever model proposed by Good, Michel and de Rafael[4]. Here the violation of CP-symmetry is also due to the W-meson. The model has the following virtues: a) a very small electric dipole moment for the neutron; b) CP-violation only in weak processes; c) only one arbitrary parameter is introduced; d) there is a large number of other observable consequences.

In this model it is assumed that the weak interactions are mediated by a triplet of W-bosons, one being charged and two neutral, in agreement with d'Espagnat's proposal[5]. The novelty here is the introduction of the neutral leptonic currents $\bar\mu\mu$ and $\bar\nu_e\nu_e$ (but not $\bar{e}e$ and $\bar\nu_\mu\nu_\mu$) coupled to the neutral bosons in such a manner that in ordinary weak processes the contributions of both bosons to the decays involving neutral leptonic currents cancel mutually. Thus the decays $K \to \pi W_2 \to \pi\mu^+\mu^-$ and $K \to \pi\mu^+\mu^-$ compensate one another. Such a compensation is possible only if the weak amplitude $K \to \pi\mu^+\mu^-$ violates CP-conservation, compared with the electromagnetic decay $K \to \pi\gamma \to \pi\mu^+\mu^-$, and if the masses of the bosons W_2 and W_3 are identically equal.

We now introduce a small mass difference between the W_2 and W_3. This mass difference can come from forces which violate SU(3), if the W-mesons have strong interactions (in pairs) with hadrons. The factor β defined as $\beta = 2(M_3 - M_2)/(M_3 + M_2)$ is a convenient characterization of the quantity of neutral leptonic current contained in the decay $K \to \pi\mu^+\mu^-$. Obviously

$$R = \frac{\Gamma(K\to\pi\mu^+\mu^-)}{\Gamma(K\to\pi\mu\nu)} \sim \beta^2.$$

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[1] Cf. the paper of P. Miller in Usp. Fiz. Nauk, 95, 470 (1968) [Sov. Phys. Uspekhi 11, (1968)]

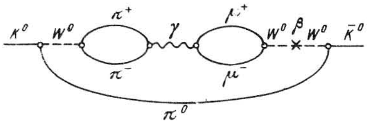

FIG. 1

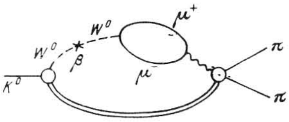

FIG 2

The experimental value is

$$R \leqslant \frac{3\cdot 10^{-6}}{3.4\cdot 10^{-2}} \sim 10^{-4},$$

which allows for a value of β of the order of 10^{-2}. The CP-violation in K-meson decays comes from diagrams containing leptonic currents coupled to W-mesons and photons (Fig. 1). In this case the violation of CP-symmetry would be of the order of $\alpha\beta$ in the mass matrix (here α is the fine structure constant), which would lead to an effect of the order of 10^{-4}, the observed magnitude being 10^{-3}. We note that in this model the amplitude for the decay $K \rightarrow 2\pi$ has a CP-odd contribution from diagrams of the form represented in Fig. 2. As regards the order of magnitude of CP-violation and the question of violation of the $\Delta I = \frac{1}{2}$ rule in the decay $K_L \rightarrow 2\pi$, it is hard to make a definite statement. There is always the possibility that one discovers that the decay $K \rightarrow 2\pi$ is forbidden in the limit of exact SU(3) symmetry, and I cannot indicate how this fact will be reflected on the order of magnitude of all other phenomena.

For the sake of completeness, here is the weak interaction Lagrangian proposed by Good et al.:

$$\begin{aligned}\mathcal{L}_W = {} & [J_1^2 W^1 + J_2^2 W^2 + J_3^2 W^3 + i(\bar{\nu}_e \nu_e + \bar{\mu}\mu) W^2] \cos\theta \\ & + [J_1^3 W^1 + J_2^3 W^2 + J_3^3 W^3 + i(\bar{\nu}_e \nu_e + \bar{\mu}\mu) W^3] \sin\theta \\ & + i(\bar{e}\nu_e + \bar{\mu}\nu_\mu) W^1,\end{aligned}$$

where J_i^j denotes a component of the octet of vector or axial vector currents. We finish the discussion of this model with the remark that the electric dipole moment of the neutron must be very small. Other observable consequences of this model have to be considered in connection with the neutral currents. A detailed discussion can be found in the original article.

We now consider the a-particle model proposed by T. D. Lee[1]. He indicated the possibility of the existence of a new set of particles called a-particles, which interact with the hadrons in a C-noninvariant manner. Thus, for instance, in the diagram of Fig. 3, which illustrates a system of particles which is even under C, the dependence on the energy of the a^+ particle may differ from the dependence on the energy of the a^- particle. A new operation, C_{st}, is defined, which for ordinary hadrons coincides with the operation of charge conjugation. However C_{st} transforms a^+ into a^+ and a^- into a^-. It is assumed that the strong interactions are invariant under this operation. It is obvious that for any process in which a-particles are neither emitted nor absorbed, C_{st} coincides with C, and C is conserved in strong interactions. However, the electromagnetic interactions change the situation.

Let us consider the diagram in Fig. 4, where the interaction of the photon with the a-particle is considered C-violating. The photon is the means by which the difference in the energy-dependences of the a^+ and a^- can be detected.

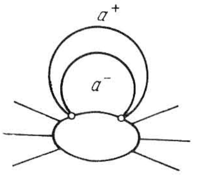

FIG 3

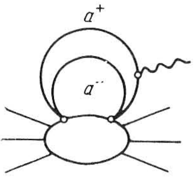

FIG 4

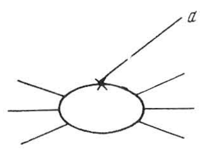

FIG 5

The model described above satisfies the $\Delta I = 0$ rule for the C-violating photon-hadron interaction.[3]. As an example let us consider a process in which an a-particle is emitted (Fig. 5). Under C_{st} all charges, except that of a^+, change their signs. Therefore the conservation of charge interdicts this process if C_{st} is conserved. Similarly, a group of a-particles cannot carry away charge if C_{st} is a good symmetry. Further, isospin invariance implies that a system of a-particles interacts like an isoscalar. But this assertion contains a loophole. Let us assume that there exist two isotriplets: a^+, a^0, a^- and b^+, b^0, b^-, and that in addition, the strong interactions are invariant under C_{st} which coincides with C for ordinary hadrons, whereas the a- and b-particles transform under C in the following manner:

$$a^+ \rightarrow b^-, \qquad a^0 \rightarrow b^0, \qquad a^- \rightarrow b^+.$$

In this case the $\Delta I = 0$ rule is not necessarily valid for the C-violating photon vertices. It is possible that this model is overly simple in the sense that minimality and C_{st}-invariance may lead to C_{st} conservation also in the electromagnetic interactions, but we do not wish at this moment to consider this possibility.

There has been an attempt to identify the a-particle with the W-meson of weak interactions[6]. As long as the weak interaction vertex between the W-boson and hadrons is subject to the ordinary CP-invariance, nothing speaks against such an identification. However an attempt was made to construct a theory in which this vertex would also be $C_{st}P$-symmetric. The difficulty consists in selecting a suitable operation C_{st}. In the recent paper by Pakvasa, Tuan and Wu[7] such an operation is introduced, by combining the C_{st} discussed above (which takes a^+ into a^+ and a^- into a^-) with a transformation from the group SU(3) such that in the W-hadron vertex charge is conserved and a Cabibbo type interaction remains valid. In addition, the charged leptons are interchanged with their respective neutrinos. More precisely, an operation T_{st} (equivalent to $C_{st}P$) is introduced, for which the action can be exhibited on the quark model. Consider the interaction Lagrangian

$$\mathcal{L} = G J_\lambda W_\lambda^* + \text{h.c.},$$

where

$$\begin{aligned}J_\lambda = {} & i(\bar{\psi}_2 \cos\theta + \bar{\psi}_3 \sin\theta)\gamma^\lambda(1+\gamma_5)\psi_1 \\ & + i\bar{\psi}_e\gamma^\lambda(1+\gamma_5)\psi_{\nu_e} + i\bar{\psi}_\mu\gamma^\lambda(1+\gamma_5)\psi_{\nu_\mu}.\end{aligned}$$

Here θ is the Cabibbo angle. Up to trivial factors related to the spinor properties of the three quark fields ψ_1, ψ_2 and ψ_3 the particle fields transform as follows under T_{st}:

$$W_\mu \leftrightarrow W_\mu^* \qquad (W_\mu^* \equiv (-1)^{\delta_{\mu 4}} W_\mu^+),$$

$$\nu_e \leftrightarrow e, \qquad \nu_\mu \leftrightarrow \mu,$$

$$\psi_1 \leftrightarrow \psi_2 \cos\theta + \psi_3 \sin\theta.$$

Indeed, the total Lagrangian can be invariant under this operation if the masses of ν_e and e, and also of ν_μ and μ, coincide, and if there are no forces which violate SU(3). Thus, CP is conserved in weak interactions, and the CP-violating effects are related to the SU(3)-violating interactions. This seems unlikely since CP-violation in weak interactions is of the order of 1% or less, whereas the effects of SU(3)-violation seem to be of the order of 10%. Let us however consider this problem in more detail. The operation which leaves the weak interactions invariant is usual charge conjugation (for all particles except the W-boson), multiplied by a rotation in the space of the fundamental representation of the group SU(3):

$$\begin{pmatrix} 0 & \cos\theta & \sin\theta \\ \cos\theta & -\sin^2\theta & \sin\theta\cos\theta \\ \sin\theta & \sin\theta\cos\theta & -\cos^2\theta \end{pmatrix}.$$

If the Cabibbo angle θ vanishes, this transformation reduces to an isospin rotation (by 180° around the first axis), which affects the pseudoscalar mesons in the following manner:

$$\pi^+ \leftrightarrow \pi^-, \quad K^+ \leftrightarrow K^0, \quad K^- \leftrightarrow K^0, \quad \eta \leftrightarrow \eta.$$

In this case SU(3) invariance would not be necessary, isospin invariance would suffice, and C would be violated only at the level of electromagnetic interactions.

From what was said above one can conclude that in such a scheme the violation of C-symmetry would occur:

1) in electromagnetic processes with $\Delta I = 0$ (the original Lee scheme);

2) in electromagnetic corrections to weak interactions (C_{st}-violation by the usual electromagnetic interactions);

3) with a force of the order $g\theta$ where $g \sim 0.1$ characterizes the scale of SU(3)-violating interactions.

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Translated by M. E. Mayer
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