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POSSIBILITY OF LARGE CP AND T VIOLATION IN WEAK INTERACTIONS

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A recent experiment ¹⁾ has identified the $\pi^+ \pi^-$ decay of the long lived component of a neutral K beam, with a branching ratio over other charged decay modes of $(2 \pm 0.4) \times 10^{-3}$. This result gives evidence for CP violation in weak interactions ²⁾ (and also of time reversal violation, assuming the validity of the CPT theorem). It is an open question to decide whether the small experimental branching ratio implies (or is consistent with) a small or a large violation of CP symmetry. Given our ignorance in the dynamics of non-leptonic weak interactions, we feel that this problem cannot find a satisfactory theoretical solution ³⁾, but that further experimentation is needed, especially in the better understood field of leptonic decays. On general grounds large violation of CP is more palatable than a small one.

In this paper we discuss the possibility of a large violation of CP symmetry within the limits of the V-A theory of weak interactions ⁴⁾, as completed by assumptions of definite SU_3 ⁵⁾ behaviour of weak currents ^{5),6)} and of the non-leptonic Lagrangian ^{7),8),9)}.

The scheme obtained in this way is not in disagreement with presently available data, including the precise measurements on the decay of the free neutron ^{10),11)}. The scheme gives also precise indications of experiments where relatively large T violation effects could be found.

In the following we will assume strict validity of the CPT theorem. The two-component nature of the neutrino puts strong limits on the violation of CP by lepton currents ; we shall assume that they are still given by

$$J_\lambda = (\bar{\mu} \gamma_\lambda (1 + \gamma_5) \nu_\mu) + (\bar{e} \gamma_\lambda (1 + \gamma_5) \nu_e) \quad (1)$$

so that CP violation should be restricted to the weak currents of strongly interacting particles ¹²⁾. Our basic assumptions will be that : weak currents are members of a single octet of Hermitian currents, J_λ^i

$$J_\lambda^i = J_\lambda^{i*} \quad (i = 1, 2, \dots, 8) \quad (2)$$

2.

J_λ^* being equal to J_λ^+ for $\lambda = 1, 2, 3$, and to $-J_\lambda^+$ for $\lambda = 4$. We also assume that : the non-leptonic Lagrangian $\mathcal{L}_{NL}$ is member of an octet L^i

$$L^i = d_{\ell m} J_\lambda^\ell J_\lambda^m \quad (3)$$

$\mathcal{L}_{NL}$ can be any combination of L^3, L^8, L^6, L^7 , but since a L^7 component can be eliminated by a transformation $e^{i\alpha Y}$ (redefinition of the relative phases of particles with different hypercharge), we put here

$$\mathcal{L}_{NL} = a L^3 + b L^8 + c L^6 \quad (4)$$

If the J_λ^i have definite CP behaviour ¹³⁾, i.e.,

$$\text{CP } J_\lambda^i (\text{CP})^{-1} = \eta(i) J_\lambda^i \quad \begin{array}{l} \text{for } \lambda = 1, 2, 3 \\ \text{(for } \lambda = 4, \text{ a minus sign)} \end{array} \quad (5)$$

where $\eta = +1$ for $i = 2, 3, 5, 6, 8$, and $\eta = -1$ for $i = 1, 4, 7$, the octet L^i also transforms in the same way, and $\mathcal{L}_{NL}$ conserves CP.

Therefore, under our assumptions, a CP violation in non-leptonic decays requires the currents J_λ^i to have mixed CP behaviour. Let us divide J_λ^i into a "regular" part $J_\lambda^{i,R}$ and an irregular part $J_\lambda^{i,I}$ (each of them a mixture of axial and vector)

$$J_\lambda^i = J_\lambda^{i,R} + J_\lambda^{i,I} \quad (6)$$

where

$$\left. \begin{array}{l} \text{CP } J_\lambda^{i,R} (\text{CP})^{-1} = \eta(i) J_\lambda^{i,R} \\ \text{CP } J_\lambda^{i,I} (\text{CP})^{-1} = -\eta(i) J_\lambda^{i,I} \end{array} \right\} \begin{array}{l} \text{for } \lambda = 1, 2, 3 \\ \text{opposite for } \lambda = 4 \end{array} \quad (7)$$

The Lagrangian for weak leptonic interactions will be given by

$$\frac{g}{\sqrt{2}} \left(J_\lambda l_\lambda + J_\lambda^* l_\lambda^* \right) \quad (8)$$

where J_λ is a member of the octet J_λ^i (6)

$$J_\lambda = \cos \theta (J_\lambda^4 + i J_\lambda^2) + \sin \theta (J_\lambda^4 + i J_\lambda^5) \quad (9)$$

According to Eq. (6) we divide J_λ into a regular and an irregular part : we have

$$(CP) \left[(J_\lambda^R + J_\lambda^I) l_\lambda \right] (CP)^{-1} = (J_\lambda^{R*} - J_\lambda^{I*}) l_\lambda^* \quad (10)$$

the Lagrangian (8) violates CP and T. Physical effects of violation will arise from the interference of the regular and the irregular part.

The behaviour of J_λ^R and J_λ^I under SU_3 and CP has interesting consequences for their matrix elements - in the case of beta decay of baryons (both $\Delta S = 0$ and $\Delta S = 1$), one gets the following theorem : the regular and irregular parts of the current give rise to different kinds of matrix elements, according to the Table

	Regular	Irregular
Vector	$\gamma_\lambda, \quad \sigma_{\lambda\nu} k_\nu$	ik_λ
Axial	$\gamma_\lambda \gamma_5, \quad k_\lambda \gamma_5$	$i \sigma_{\lambda\nu} k_\nu \gamma_5$

TABLE

This theorem is valid for $\Delta S = 0$ transitions up to electromagnetic corrections, while for $\Delta S = 1$ it is only valid up to SU_3 breaking interactions. The proof is simple and will be omitted here. According to this theorem the CP conserving part of the current gives rise to the normal four terms in the beta decay amplitude, while the CP violating part gives rise to two further terms ¹⁴⁾. Time reversal violation arises from the interference of "regular" and "irregular" terms, which are out of phase by 90 degrees. However, the latter give only first forbidden contributions to the matrix element, so that T violation should be exceedingly small in beta decay with low Q value, particularly in the case of the decay of free neutrons, where a good upper limit exists on the amount of T violation ¹⁰⁾.

A direct consequence of the 90° shift among regular and irregular terms is that no interference among the two is to be expected in T conserving effects like spectra, decay rates, up-down asymmetries, longitudinal polarizations, etc. In all these effects the irregular terms give only second-forbidden contributions, and relatively large coefficients are certainly consistent with existent data.

To observe T violating effects one should look for $\vec{J} \cdot \vec{p}_1 \times \vec{p}_2$ or $\vec{p} \times \vec{q}_1 \cdot \vec{q}_2$ correlations in high Q value beta decays, in particular the beta decays of hyperons ¹⁵⁾, or in muon capture experiments, or in neutrino experiments.

A very interesting case is that of $K \rightarrow \pi + \mu + \nu$ decays. In this case the matrix element contains two terms :

$$\left[(P_{\lambda}^K + P_{\lambda}^{\pi}) + \frac{\epsilon}{2} (P_{\lambda}^{K^*} - P_{\lambda}^{\pi^*}) \right] (\bar{u}_{\mu} \gamma_{\lambda} (1 + \gamma_5) u_{\nu}) \quad (11)$$

In the limit of exact SU_3 the two terms arise respectively from the regular and the irregular parts of the current, and are out of phase by 90° , so that ξ should be purely imaginary. Many recent experiments point to a small value of the real part of ξ , but little is known on the imaginary part. In this process the irregular part of the current is not as depressed by kinematical reasons as in beta decay, so that sizeable T violation can be expected in the form of a non-zero polarization of the muon perpendicular to the decay plane ¹⁶⁾.

Even if the experiment in Ref. ¹⁾ will find other interpretations than CP violation, it is interesting to note that no other experiment exists at present which excludes a large CP violation in weak interactions, so that some of the experiments indicated above should be seriously considered.

REFERENCES AND FOOTNOTES

- 1) J.H. Christenson, J.W. Cronin, V.L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).
- 2) Other more exotic interpretations are possible ; J. Bernstein, T.D. Lee, and the author of this note have considered the possibility of long range forces different from the electromagnetic and gravitational ones and discussed the experimental implications of their existence (to be published).
- 3) For example we do not understand why certain weak decays like $\Sigma^- \rightarrow n + \pi^-$ are nearly parity conserving.
- 4) R.P. Feynman and M. Cell-Mann, Phys. Rev. 109, 193 (1958).
R.E. Marshak and E.C.G. Sudarshan, Proceedings of the Padua-Venice Conference on Mesons and Recently Discovered Particles (Società Italiana di Fisica, Padua-Venice, 1958).
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Y. Ne'eman, Nucl. Phys. 26, 222 (1961).
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- 8) B.W. Lee, Phys. Rev. Letters 12, 83 (1964).
- 9) M. Gell-Mann, Phys. Rev. Letters 12, 155 (1964).
- 10) M.T. Burgy, V.E. Krohn, T.B. Novey, G.R. Ringo, and V.L. Telegdi, Phys. Rev. Letters 1, 324 (1958).
- 11) Other tests of CP, including the measurements of electric dipole moments, are not conclusive against a large CP violation in weak interactions.

- 12) CP violating effects could be introduced into the lepton current, (preserving the two-component hypothesis), by means of derivative couplings of the form $\bar{\ell}(p_{\lambda}^{\ell} - p_{\lambda}^{\nu})(1 + \gamma_5)\nu$ or $\bar{\ell}(p_{\lambda}^{\ell} + p_{\lambda}^{\nu})(1 + \gamma_5)\nu$, where $\ell = e$ or μ . A good limit on the latter kind of current can be obtained from the experimental value of the $\pi^+ \rightarrow e^+ + \nu / \pi^+ \rightarrow \mu^+ + \nu$ ratio.
- 13) The definition of charge conjugation in the frame of SU_3 is discussed in Ref. 7). The definition of CP follows along similar lines.
- 14) A similar classification of terms has been introduced by S. Weinberg, Phys. Rev. 112, 1375 (1958). According to Weinberg's nomenclature, the irregular part of J_{λ} with $\Delta S = 0$ is a "second class" current. Weinberg's classes are defined by the operation $CP e^{i\pi I_2}$, IInd class currents having opposite behaviour from Ist class current. In our case we are specifying that irregular terms are second class in a definite way; they have opposite CP but the same behaviour under charge symmetry. This is essentially the content of Eq. (2) which ensures that the $\Delta S = 0$ part of J_{λ} and its Hermitian conjugate belong to the same triplet. The octet condition extends the validity of the Table from the case of $n \rightarrow p$ transitions (for which it can be readily derived by Weinberg's method) to the general case, including $\Delta S = 0$ transitions like $\Sigma^+ \rightarrow \Lambda + e^+ + \nu$, and $\Delta S = 1$ transitions like $\Lambda \rightarrow p + e^- + \bar{\nu}$, etc..
- 15) A particularly convenient case is the study of a $\vec{p}_{\Lambda} \times \vec{p}_e \cdot \vec{\sigma}_{\Lambda}$ correlation in $\Sigma^{\pm} \rightarrow \Lambda + e^{\pm} + \nu$. This transition has an high Q value compared to normal beta decay, and the Λ polarization can be measured directly from its decay.
- 16) This test of T reversal invariance was originally proposed by J.J. Sakurai, Phys. Rev. 109, 980 (1958).