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CP VIOLATION OUTSIDE THE $K^0\bar{K}^0$ SYSTEM (*)

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Abstract. In these notes, I am going to present a review of the existing experimental evidence for CP conservation outside the $K^0\bar{K}^0$ system. Some theoretical speculations are added.

There is essentially nothing new in this domain during the last years. There is no conclusive experimental evidence for any CP violation anywhere outside the $K^0\bar{K}^0$ system. On the other hand no new attractive theoretical ideas have been proposed. Therefore I shall just present a very brief review of the relevant experimental situation and at the end I shall add some remarks on possible theoretical models.

1. TCP. — Theorists are very sensitive to the validity of the so-called TCP theorem. They have good reasons to believe that all interactions are invariant under the operation $\Theta$, which is defined as the product of the operators $P$, $C$ and $T$ (parity, charge conjugation and time reversal) taken in any order. The TCP theorem can be shown to follow from the general axioms of local quantum field theory. In a simple form it states the following: Let $H$ be a local hermitian Hamiltonian, invariant under proper Lorentz transformations, which describes the interaction between a number of fields $\Phi_i(x)$. Under the action of the operators $P$, $C$ and $T$, $\Phi_i(x)$ transform in the usual way. For example, for spin zero particles, we have:

- $P \Phi(x, t) P^{-1} = \eta_P \Phi(-x, t)$
- $C \Phi(x, t) C^{-1} = \eta_C \Phi^+(x, t)$
- $T \Phi(x, t) T^{-1} = \eta_T \Phi(x, -t)$

where $+$ means hermitian conjugate. Analogous formulae hold for any spin. The phases $\eta_P$, $\eta_C$ and $\eta_T$ have absolute values equal to unity and characterize the intrinsic transformation properties of the fields. For example $\eta_P = -1$ for a pseudoscalar field. The TCP theorem then states that there always exists a choice of phases $\eta_P$, $\eta_C$ and $\eta_T$, for the various fields (usually in more than one way) with the following properties:

a) $H$ commutes with $\Theta$;

b) if with this choice $H$ does not commute with $P$, it will not do so with any other choice and the theory will not conserve parity. The same is true for $C$ and $T$.

In the following we shall state some of the consequences of the TCP theorem.

a) The mass of a particle is equal to the mass of its anti-particle. The best evidence for such an equality is given by the mass difference $m_{K^0} - m_{\bar{K}^0}$

$$m_{K^0} = \langle K^0 | H | K^0 \rangle$$

$$m_{\bar{K}^0} = \langle \bar{K}^0 | H | K^0 \rangle .$$

This difference cannot be measured directly but one shows that it is bounded by $m_{\pi} - m_{\mu}$, the mass difference between the short- and long-lived neutral kaons. So one gets an accuracy of:

$$\left| \frac{m_{\pi} - m_{\mu}}{m_K} \right| \sim 6.5 \times 10^{-15} .$$

This gives the upper limit of TCP violation in strong interactions. The electromagnetic contributions to the kaon mass are expected to be of the order of $10^{-7}$.

b) The lifetime of any particle equals that of its anti-particle. The sensitivity there is of the order of $10^{-3}$ for all parts of the weak interaction.

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The results check the leptonic as well as the \( \Delta S = 0 \) and \( \Delta S = 1 \) parts of the weak interactions. Notice however that the accuracy is of the order of the observed CP violation.

c) The magnetic moment of a particle equals that of its antiparticle. The results on muons and electrons provide good limits for the electromagnetic interactions of leptons:

\[
\begin{align*}
    g_\mu^+ - g_\mu^- &= (1.2 \pm 1.4) \times 10^{-6} \\
    g_e^+ - g_e^- &= (16.2 \pm 21.6) \times 10^{-6}.
\end{align*}
\]

In the following we shall assume TCP invariance and we shall talk without distinction about CP or T violation.

2. CP or T violation in strong or electromagnetic interactions. — The observed selection rules in nuclear physics indicate that parity is very well conserved in both strong and electromagnetic interactions. Furthermore we just saw that CPT is also in very good shape for these interactions. Therefore, a violation of C implies that of T and vice versa. There is a special interest for possible C-violation in electromagnetic interactions. The experimental situation was reviewed in ref. [1], and we refer there for a more detailed account as well as for references to the original papers. Little has been added since. The essential results are the following:

a) Tests of the principle of detailed balance in nuclear reactions, as well as measurements of the spectra of positively and negatively charged pions and kaons in \( p\bar{p} \) annihilations, show that the possible T-violating amplitudes in strong interactions are smaller than 1%.

b) With regard to \( \eta \) decays again no significant progress since 1968. The decay \( \eta \to \pi^+ + \pi^- + \pi^0 \) has not been observed with an upper limit of the branching ratio 2.3 \( \times 10^{-3} \). Notice that this alone does not rule out a large T-violation in electromagnetic interactions because it depends on the isospin properties of the C-even part of the current and the decay is inhibited by SU(3) and angular momentum barriers. The last experiments on the spectra of \( \pi^+ \) and \( \pi^- \) in \( \eta \to \pi^+ \pi^- \pi^0 \) and \( \eta \to \pi^+ \pi^- \gamma \) seem to indicate a small effect but it has only been observed by one group and the results are compatible with zero within three standard deviations. More work is required before any conclusions can be drawn.

c) There exist some recent experiments which test T-violation in electromagnetic interactions. I will give their results because they are too recent to be included in ref. [1].

c1) Two groups have measured independently the \( ep \) inelastic cross-section in the resonance region using polarized proton targets [2]. Only the final electron was observed.

Let \( \sigma_+(\sigma_-) \) denote the differential cross section \( d\sigma/dE' d\theta \) with the spin of the target parallel (anti-parallel) to the scattering plane. \( E' \) and \( \theta \) are the energy and angle of the final electron. T-violation would produce an asymmetry of the form:

\[
A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}.
\]

The results from both groups are compatible with zero asymmetry and rule out a maximal T-violation in the \( \gamma NN^* \) vertex. The experiments cover the region up to the third resonance and therefore they test both the isovector and isoscalar parts of the electromagnetic current.

c2) Tests of the principle of detailed balance were made for the reaction [3]

\[
n + p \leftrightarrow d + \gamma.
\]

The results are in good agreement with detailed balance in all measured energies suggesting no effect of T-violation.

c3) The differential cross section for the reaction \( \pi^- + p \to \gamma + n \) was measured [4] and compared with the existing data on \( \pi^- \) photoproduction on deuteron. The experiment was performed at three values of incident pion momenta 316 MeV/c, 450 MeV/c and 490 MeV/c. The angular distributions at the two higher energies agree well with detailed balance but at 316 MeV/c and at angles \( \theta_{\pi} \gtrsim 90^\circ \), there seems to be a descrepancy. The photoproduction cross sections seem to be about 30% higher. However the errors are quite large and, given the theoretical uncertainties in extracting the neutron cross sections out of the deuteron data, it does not seem to me that the effect is very significant. The authors of ref. [4] attempt a fit of the data assuming a T-violating phase. In all their solutions, except one, this phase turns out to be compatible with zero within two standard deviations.

d) Finally there are the measurements on the neutron electric dipole moment. The last (1968) results is \( \mu/e = (2 \pm 2) \times 10^{-23} \) cm. Notice that, on dimensional grounds, if the T-violation was maximal in electromagnetic or strong interactions, one would expect a result of the order of \( 10^{-19} \) cm.

From all these results we conclude that we have still no conclusive evidence of a large C-violation in either electromagnetic or strong interactions.

3. CP or T-violation in weak interactions. — We are going still to assume TCP invariance, although, as
we have seen, it is not so well established for all parts of the weak interaction.

CP violation in weak interactions can manifest itself in different ways. One is a possible phase between the vector and the axial currents, a theory like \( V + e^{i\phi} A \) instead of the usual \( V-A \). The angle \( \phi \) has been measured in neutron as well as in nuclear \( \beta \) decay and the result agrees with 180° with an error of 1°-2°. For the strangeness changing \( \beta \) decays of hyperons, there are no available experimental results but we heard here that with the improved hyperon beams some progress can be expected. In non-leptonic hyperon decays there are some results from the decay \( A \to p + \pi \). The phase of the final state was measured and compared with the \( \pi-N \) scattering phase shift. No effect was found but the errors are quite large.

There is one new experiment [5] on a comparison of the Dalitz plot distributions of 1.6 million of \( \pi^+ \) decays and an equal number of \( \pi^- \). No significant asymmetry was found in any region of the plot. In terms of the slope parameters \( a_+ \) and \( a_- \) they find

\[
A = \frac{a_+ - a_-}{a_+ + a_-} = -0.007 \pm 0.005 \text{ 3}.
\]

In the leptonic \( K \) decays we have measurements of the transverse polarization of muons. No effect has been found but in \( K_{3\pi} \) decays we have a pure vector transition and an effect of the form \( V + e^{i\phi} A \) could not be seen. Furthermore we learnt in this meeting to be very careful towards results coming from \( K_{3\pi} \) decays.

This ends the brief review of the experimental situation. CP violation has only been found, up to now, in the \( K^0-\bar{K}^0 \) system. Furthermore, the present limits do not allow a distinction between a superweak model and a millistrong or milliweak one.

4. Some theoretical considerations. — As I told you already, there exists no theory of CP violation which could be called, by any stretch of imagination, esthetically attractive. Therefore I do not defend, and I do not advocate any of the models I am going to discuss. They are all ugly and unnatural and I only present them in order to show you what kind of problems a theorist has to face if he wants to construct a theory of CP violation.

We saw that all experimental results are compatible with the so called «superweak» model. This means that the phenomenological Lagrangian which describes the different interactions contains a term of the form \( \lambda_{K^0-\bar{K}^0} \), where \( \lambda \) is a dimensionless coupling constant. This term induces \( K_L \to K_S \) transitions and accounts for the \( K_L \to 2\pi \) decays. Using the measured value of \( \eta_{+-} \) we find an extremely small value for \( \lambda \left( \sim 10^{-17} \right) \). It is clear that this term will have no measurable effect anywhere in Physics outside the \( K^0-\bar{K}^0 \) system. In other words, this term has no other «raison d'être» but to explain the observed \( K_L \to 2\pi \) decays. Unfortunately this characterizes all proposed models of CP violation.

One could construct models which give the same results with the superweak hypothesis without introducing terms with such small coupling constants. The CP violation may have the strength of the ordinary weak interactions if one arranges the effects to cancel in first order. One such model was the theory proposed, some years ago, by Nishijima [6]. I shall say two words about it, because it has been the source of a considerable number of wrong papers by people who misunderstood its very simple principle: Let \( \mathcal{L} \) be a Lagrangian describing interactions among some fields \( \Phi_i(x) \) and let \( J_\mu(x) \) be a vector operator constructed out of the fields \( \Phi_i(x) \). Using the equations of motion derived from \( \mathcal{L} \), we can evaluate the divergence \( \partial_\mu J_\mu(x) \),

\[
\partial_\mu J_\mu(x) = F(x)
\]

where \( F(x) \) depends on the fields \( \Phi_i(x) \) and their derivatives.

Let us now consider the Lagrangian \( \mathcal{L}' = \mathcal{L} + fF(x) \) where \( f \) is a coupling constant. If we consider \( \mathcal{L} \) as the unperturbed Lagrangian and \( fF(x) \) as a perturbation, it is clear that in the perturbation series, the first order terms vanish.

If we choose appropriately \( J_\mu(x) \), \( F(x) \) might violate CP and \( f \) can be of the order of the Fermi coupling constant. All CP violation effects will be of order \( G^2 \) and all predictions will coincide with the usual superweak theory.

Alternatively, one could introduce CP violation through the usual picture where weak interactions are mediated by vector bosons \( W_\mu \). Let \( h_0^{(0)}(x) \), \( h_0^{(1)}(x) \) and \( I_p(x) \) be the \( \Delta S = 0 \), \( \Delta S = 1 \) and leptonic currents respectively. The weak Lagrangian is given by

\[
\mathcal{L} = gW_\mu(x) \left( h_0^{(0)}(x) + h_0^{(1)}(x) + I_p(x) \right) + \text{h. c.}
\]

where the Fermi coupling constant \( G/\sqrt{2} \) equals \( g^2/M_\pi^2 \).

It is clear that no change of phase between \( h_0^{(0)} \) and \( h_0^{(1)} \) and \( I_p \) will induce a CP violation because these relative phases can be changed arbitrarily. In this model CP violation can be introduced through a phase difference between the vector and the axial parts of the current and we saw that there exist no good limits on such a phase for \( h_0^{(1)} \). Such a theory, of the form \( V + e^{i\phi} A \), would predict CP violation in hyperon decays as well as in strangeness changing neutrino induced reactions. One might try to write a model of the superweak variety by increasing the number of \( W \)'s from one to two. However it turns out that this is not possible in any easy way. In fact let us write the Lagrangian with two bosons (omitting, for simplicity, the leptonic current) as:

\[
\mathcal{L} = gW_\mu(x) \left( h_0^{(0)}(x) + h_0^{(1)}(x) \right) + \text{h. c.} + gW_\mu(x) \left( h_0^{(0)}(x) + e^{i\phi} h_0^{(1)}(x) \right) + \text{h. c.}
\]

This looks, at first sight, as a superweak model
because if $W_1$ was absent we could eliminate $e^{i\phi}$ by a change of phase of $h_\mu^{(i)}$. Therefore we might think that CP violation appears only when both $W'$s are present and hence it is of order $G^2$. However, this reasoning is wrong. If the $W'$s have different masses the amplitude at order $G$ has a momentum dependent phase and consequently violates CP. If, on the other hand, the $W'$s have the same mass we can show that there is no CP violation at any order. In order to see this, let us rewrite $\mathcal{L}$ using matrix notation:

$$\mathcal{L} = g \bar{W}_\mu(x) C h_\mu(x) + \text{h.c.}$$

where:

$$W_\mu(x) = \begin{pmatrix} W_1^+(x) \\ W_2^+(x) \end{pmatrix}$$

$$h_\mu(x) = \begin{pmatrix} h_1^{(0)}(x) \\ h_1^{(1)}(x) \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & 1 \\ 1 & e^{i\phi} \end{pmatrix}.$$  

The mass term of the vector bosons is invariant under a transformation $W_\mu(x) \to U W_\mu(x)$ where $U$ is an arbitrary unitary $2 \times 2$ matrix. Now it is easy to show that for an arbitrary $2 \times 2$ matrix $C$, one can find a $2 \times 2$ unitary matrix $U$ and a $2 \times 2$ diagonal phase matrix $D$ of the form

$$D = \begin{pmatrix} e^{i\phi_1} & 0 \\ 0 & e^{i\phi_2} \end{pmatrix}$$

such that

$$UCD = C^*$$

where $C^*$ is the complex conjugate matrix of $C$. Therefore one can eliminate CP violation by performing a unitary transformation among the $W'$s and changing the phases of the currents. You can get around this difficulty by making the model more complicated, either by adding further $W'$s or by playing games with the form of the hadronic or leptonic currents. For example one could use a leptonic current involving more than two neutrino states along the lines presented in Prof. Glashow's talk. Another amusing possibility is to use the four quark theory that we heard yesterday [7]. I remind you that in this theory, strong interactions contained an extra conserved quantum number, besides strangeness, that we had called «charm». Like strangeness, charm is also violated by weak interactions. It is easy to change the theory in a variety of ways (unfortunately none of them attractive) so that, at first order in $G$, all CP violation occurs only in charm violating reactions. Such a theory would give for the ordinary known weak interactions the same predictions as a superweak model. But I guess that I become too science-fiction, so I better stop.

References