The Situation for *CP* Symmetry

This year marks the tenth anniversary of the otherthrow of the parity and charge-conjugation invariance principles in weak interactions. The pace of development ten years ago, one recalls, was stunning, once the theoretical possibilities had been laid out by Lee and Yang[1] and the initial experiments carried out by Wu *et al.*,[2] Garwin *et al.*,[3] and Friedman and Telegdi.[4] Within a very short time one had seen that the symmetry-violating effects were widespread, and generally large, in all branches of weak-interaction physics; and for the neutrinos in particular, the negative aspect of symmetry breakdown was replaced by the affirmative picture of the two-component theory.

More recent developments concerning the principles of CP and time-reversal (T) symmetry have been unfolding more slowly. The overthrow of CP invariance was signalled three years ago in the discovery by Christenson, Cronin, Fitch, and Turlay[5] of the rare decay process $K_L \to \pi^+ + \pi^-$. Here K_L is the longer-lived of two neutral K mesons, practically degenerate in mass. The K_L meson is known to decay prominently into three-pion states which are odd under CP. The two-pion state, on the other hand, is even under CP; hence the implication of symmetry breakdown here. (This is a parallel of the earlier evidence for *parity* violation based on the $\tau - \theta$ puzzle: the observation that charged K mesons decay in both three-pion and two-pion modes.) Alternatively, one argues that the short- and long-lived mesons, K_S and K_L, are linear combinations of K^0 and $\bar{K}^0$ which ought to have opposite CP quantum numbers in a world where CP invariance obtains—but both K_S and K_L in fact decay via two-pion modes. With CP invariance overthrown, one expects, on the basis of the still tenable and deeply held principle of CPT invariance, a breakdown also of time-reversal symmetry. The program then, three years ago, was clear enough. One must look for further evidence bearing on CP, not only in neutral K meson decays, but elsewhere too; and direct tests for the breakdown of time-reversal symmetry were very much in order.

Unfortunately, the history of ten years ago has not yet begun to repeat itself. There is still no direct and convincing evidence for T violation anywhere; and the breakdown of CP invariance is still confined to neutral K meson phenomena.

The neutral K meson system is peculiarly sensitive to delicate effects. On the usual picture, the very constitution of K_S and K_L in terms of K^0 and $\bar{K}^0$ is determined by transitions connecting K^0 and $\bar{K}^0$: either direct ones, in lowest order of $\Delta S = 2$ couplings; or indirect ones, in second order of weak interactions via real or virtual emission and reabsorption of K-meson decay products. A rather gloomy possibility, which would confine practically observable effects of CP violation solely to neutral K meson phenomena, was discussed some time ago by Wolfenstein.[6] He envisaged a superweak first-order ($\Delta S = 2$) coupling which connects K^0 and $\bar{K}^0$ and which is supposed to represent the sole source of CP violation. Such a superweak interaction would give to K_S and K_L a CP-violating constitution, but elsewhere weak processes would be CP-conserving to order of the strength of the normal weak interactions. The superweak model has however now been ruled out, in connection with the recent discovery of the CP-violating decay process $K_L \to 2\pi^0$. In the analysis of the two-pion decay modes of K_S and K_L one deals with two interesting amplitude ratios:

$$\eta_{+-} = \text{Amp}(K_L \to \pi^+ + \pi^-)/\text{Amp}(K_S \to \pi^+ + \pi^-)$$

and

$$\eta_{00} = \text{Amp}(K_L \to 2\pi^0)/\text{Amp}(K_S \to 2\pi^0).$$

The recent experiments of Gaillard *et al.*[7] and Cronin *et al.*[8] establish that $|\eta_{00}|$ is appreciably bigger than $|\eta_{+-}|$, by about a factor of two. The superweak model, however, implies the equality of η_{00} and η_{+-}. This can be seen as follows. If, as in the superweak model, CP violation arises *solely* from virtual transitions between K^0 and $\bar{K}^0$, then the amplitudes for the real (on mass shell) transitions $K^0 \to \pi^+ + \pi^-$ and $\bar{K}^0 \to \pi^+ + \pi^-$ should be equal, just as the amplitudes for $K^0 \to 2\pi^0$ and $\bar{K}^0 \to 2\pi^0$ must be equal. But this implies the equality of η_{+-} and η_{00}, whatever the constitution of K_S and K_L may be in terms of K^0 and $\bar{K}^0$. The observation of a difference between η_{+-} and η_{00} thus demonstrates the occurrence of CP violation for on-mass-shell two-pion decay modes, and, incidentally, violation of the $\Delta I = \frac{1}{2}$ rule. The magnitudes and phases of η_{+-} and η_{00} represent four parameters which are clearly of fundamental interest[9] and we may expect their determinations to become increasingly accurate in the near future. The encouraging note is that CP violation now emerges as a real, on-mass-shell effect; and this provides impetus to a search for its workings in other physical processes.

Regarding the fundamental location of CP breakdown, a number of different sites have been advocated, apart from the superweak. One natural arena for the breakdown of symmetries would appear, on the basis of past history, to be at the level of the usual weak interactions themselves—or rather, at a somewhat lower level (order of η_{+-} or η_{00}; i.e., order of 10^{-2}–10^{-3}) among the $\Delta S = 1$ nonleptonic weak interactions. On this view *CP*-violating effects of this order would be expected for nonleptonic weak reactions generally. Whether similar effects occur also in the semileptonic interactions would of course be, and in any case is, an equally important question. A distinctly different possibility, first discussed by Lee and Wolfenstein,[10] attributes the *CP* breakdown observed in weak decays to small *C*- and *T*-violating terms in the "strong" interactions ($\Delta S = 0$, parity conserving), the characteristic strength relative to that of the strong, symmetry-preserving terms being again of order 10^{-2}–10^{-3}. Here one is led to expect *CP*- and *T*-violating effects to this order generally for all strong, electromagnetic, and weak reactions involving hadrons. For the strong and electromagnetic reactions, which are known to be parity-preserving to a much higher order of accuracy, *C* and *T* violations of order 10^{-2}–10^{-3} cannot be ruled out on the basis of present evidence.

Still classifying possibilities according to broad categories, one can finally imagine, with Bernstein, Feinberg, and Lee,[11] and with Barshay,[12] that *substantial* *C* and *T* violation occurs in the electromagnetic interactions of the hadrons. The "usual" electromagnetic current is odd under charge conjugation. If there is an even part which is in some sense of comparable strength, the electromagnetic corrections would induce *CP*- and *T*-violating effects, of order 10^{-2}–10^{-3} (i.e., order of the fine-structure constant) in both strong and weak interactions. But in electromagnetic reactions involving hadrons, the symmetry-breaking effects could well be substantial. Remarkably enough, this is still largely an open experimental possibility,[11] although present evidence in η decay is not encouraging.

What the above discussion amounts to is only a rough classification of alternatives. On the theoretical side one can certainly write down, say in the framework of Lagrangian field theory, interaction terms which exemplify each possibility; indeed, with a little carelessness one can easily destroy *CP* invariance even without meaning to do so. Where hadrons are concerned, however, there is no reliable way to go from the details of a model to the details of its physical implications, apart from the symmetry properties built into the model. At the present stage then, one is forced to deal in general categories and orders of magnitude. The failure to detect an anticipated effect of symmetry breakdown needn't be conclusive, until failure becomes pervasive over a variety of tests. But affirmative results are always best!

Tests of *CP* and *T* invariance are easily conjured up. Let us illustrate some of the main features by means of examples, a few of which are of current practical interest. Consider first the principle of *CP* invariance.

In general terms, this principle implies that any given process and its CP-conjugate analog (each particle is replaced by its antiparticle, and all momentum three-vectors are reversed) should proceed with identical differential rates. If the initial and final states of an imagined reaction are self-conjugate one obtains restrictions on the reaction itself. Thus: (i) the π^0 meson, which decays predominantly into two photons, cannot decay into three or any odd number of photons; (ii) $\eta^0 \to 2\pi^0 + \gamma$ decay is similarly forbidden, as is $\eta^0 \to \pi^0 + e^+ + e^-$ decay, to lowest order in electromagnetic interactions; (iii) the decay spectra in the processes $\eta^0 \to \pi^+ + \pi^- + \pi^0$ and $\eta^0 \to \pi^+ + \pi^- + \gamma$ must be symmetric under the interchange $\pi^+ \rightleftarrows \pi^-$; (iv) etc. When the states involved in a given reaction are not self-conjugate, then CP invariance acts to relate the reaction in question to a distinct conjugate reaction. For example, CP invariance implies the equality of partial lifetimes and decay spectra for the processes $K^+ \to \pi^+ + \pi^+ + \pi^-$ and $K^- \to \pi^- + \pi^- + \pi^+$. Here one must mention the implications of CPT invariance. This symmetry principle, taken alone, entails the equality of *net* decay rates—summed over all final states—for particle and antiparticle. Equality of partial rates follows from CPT alone only if final-state interactions can be neglected. Thus, with neglect of electromagnetic corrections CPT invariance implies the equality of the partial rates for, say, $K_{\mu 2}{}^+$ and $K_{\mu 2}{}^-$ decays; similarly for $K^+ \to \pi^+ + \pi^0$ and $K^- \to \pi^- + \pi^0$ decays (here, in the absence of electromagnetic effects, the two pions can scatter only into themselves). To this order too, the partial rates for K^+ decay summed over the $\pi^+\pi^+\pi^-$ and $\pi^0\pi^0\pi^+$ channels should be the same as for K^- decay summed over the corresponding three-pion channels. But unless final-state strong interaction effects are negligible for the three-pion systems here, CPT invariance does not guarantee equality of the *sub* partial rates, say, for $K^+ \to \pi^+\pi^+\pi^-$ and $K^- \to \pi^-\pi^-\pi^+$ decays; even less does it guarantee the identity of their decay spectra. For these coincidences one needs CP invariance (or special dynamical inhibitions or "accidents," always possible).

The principle of time-reversal invariance, applied to collision processes, leads to reciprocity relations: equality of the differential rates for the two processes $i \to f$ and $f^\tau \to i^\tau$, where the time-reversed states f^τ and i^τ are the same as the corresponding states f and i, except that all spins and momenta are reversed. Detailed analyses of reciprocity relations, especially for electromagnetic processes, can be found in the papers of Christ and Lee.[13] For weak, semi-leptonic processes, such as the three-body β-decay reactions $n \to p + e^- + \nu$, $\Lambda \to p + e^- + \nu$, $K^+ \to \pi^0 + \mu^+ + \nu$, final-state interactions arise only from electromagnetic effects. To the extent that such effects can be ignored (i.e., to order of the fine-structure constant), time-reversal invariance forbids the appearance of correlations of the form

$\boldsymbol{\sigma} \cdot \mathbf{k}_1 \times \mathbf{k}_2$, where $\boldsymbol{\sigma}$ is the spin polarization of any one of the Fermions involved in the reaction and $\mathbf{k}_1$ and $\mathbf{k}_2$ are any two independent momentum vectors. The absence of such correlations has already been established to fairly high accuracy for neutron and $K_{\mu 3}$ β-decays. In the nonleptonic hyperon decays, e.g., $\Lambda \rightarrow N + \pi$, final-state interaction effects are in general not negligible. Here time-reversal invariance implies definite phase relations between the s- and p-wave amplitudes, these relations being determined by the strong final-state scattering phase shifts. Present evidence gives no indication of T violation.

One of the most dramatic evidences of time-reversal breakdown imaginable would manifest itself in the form of a nonvanishing electric-dipole moment for the neutron. Such a moment can arise only to the extent that both time-reversal and parity violating effects conspire—in this strangeness-preserving situation! Here we are in as much ignorance with regard to the parity aspect of the matter as with the time-reversal part. That is, there does not yet exist convincing evidence for parity violation in strangeness-preserving interactions. The electric-dipole experiments now underway should therefore illuminate several major questions all at once—one way or another!

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