CAN *CP* INVARIANCE BE SAVED?

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We examine the experimental basis for the generally accepted statement that lingering 2π decays from a neutral kaon beam imply that *CP* invariance must be abandoned. We find that, apart from formulations which cannot be distinguished physically from theories admitting *CP* noninvariance, no *CP*-invariant description seems possible within the context of quantum theory. If quantum mechanics is disregarded, K^0-decay experiments do not necessarily contradict *CP* invariance. A crucial test is proposed for that case.

A recent paper[1] describes a *CP*-invariant theory of $K^0 \to 2\pi$ decays and argues, despite its title, that "until this model has been disproven experimentally, there is no rigorous experimental proof that *CP* invariance is violated." The present note summarizes the evidence that that model has been disproved and that no theory is likely to reconcile the observed phenomena with the hypothesis of *CP* invariance.

Lipkin's paper describes a particular case of the general class of particle-mixture theories of $K^0 \to 2\pi$ decay, which have been reviewed already in this journal,[2] without extending the earlier discussion in any essential respect. We shall here adopt a more general viewpoint in examining the relation between $K^0 \to 2\pi$ decays and *CP* invariance. The relevant arguments have all appeared previously in the literature. They are collected and presented here because the publication of Ref. 1 shows that they are not as widely known as one thought; a concise summary may therefore serve some purpose.[3]

The *CP*-even and *CP*-odd components of a neutral-kaon beam, satisfying $CP|K_\pm\rangle = \pm|K_\pm\rangle$, must decay independently[4] to *CP* eigenstates with eigenvalues ±1, respectively, if *CP* invariance holds.[5] According to the principles of local quantum field theory,[6] if *CP* invariance holds, a neutral 2π state has $CP = +1$. Therefore, only the K_+ component should decay into two pions. The originally discovered K_1^0 component, with the lifetime $\tau_1 = 8.5\times10^{-11}$ sec, which decays predominantly through 2π channels, should then be identified with K_+, and the other long-lived K_2^0 component ($\tau_2 = 5.6\times10^{-8}$ sec) should be K_- and therefore not have any 2π decay modes. It has been found[7] that $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes persist at times $\tau \sim 300\tau_1$—a phenomenon we shall call the LLD effect—when the K_1^0 component should have decayed to a negligible level. If this is interpreted as evidence for 2π decays of the other component K_2^0, the hypothesis of *CP* invariance must clearly be invalid.

Efforts were made to avoid this conclusion by attributing the LLD effect to decays of particles other than kaons in the neutral beam[8] or to decays of kaons into particles which are not pions.[9] These were excluded when it was shown[10] that the long-lived $\pi^+\pi^-$ decays interfered constructively with the $\pi^+\pi^-$ decays of K_1^0's regenerated by a material absorber in the beam. This observation also eliminated the attempt to explain the LLD effect as the decay of K_2^0 into a *CP*-antisymmetric $\pi\pi$ state, which could exist through an arbitrary relaxation of the rules of quantum field theory.[11] The interference effect established that the state L responsible for LLD decays was coherent with the K_2^0 from which the K_1^0 was regenerated, and the simplest interpretation, which is the one usually made, is that $L \equiv K_2^0$.

From a strictly logical point of view, such an identification requires that all properties of L should coincide with those of K_2^0. (i) The lifetime associated with LLD decays is known to agree with the K_2^0 lifetime within an accuracy of about 50%.[12] Under certain plausible assumptions, the agreement holds to better than 25%.[13] (ii) The mass difference between K_1^0 and L, measured by the time dependence of the interference between LLD and regenerated $K_1^0 \to \pi^+\pi^-$ decays behind a regenerator,[14] agrees within $0.1/\tau_1$ (i.e., within $\Delta m/m \sim 10^{-15}$!) with the K_1^0-K_2^0 mass difference measured by methods which do not depend upon the occurrence of LLD decays.[15] (iii) One should also compare the interaction lengths of L and K_2^0 in different materials.[16,2] If $L \equiv K_2^0$, LLD events should be attenuated at the same rate as any individual channel of K_2^0 decay, when an absorber is interposed (far upstream to avoid complications from regeneration) in a neutral-kaon beam. That the branching ratio P for $\pi^+\pi^-$ decays with respect to all charged modes of K_2^0 decay appears to be unchanged whether one uses 4 cm [13] or 7.5 cm [17] of lead to clear the kaon beam of γ rays shows that the interaction lengths of L and K_2^0 cannot be very different. If increasing the amount of absorber by D, in units of K_2^0 interaction lengths, results in a small fractional change in P, the difference $\Delta\lambda$ between the interaction length λ of L and the K_2^0 interaction length is given by

$$\Delta\lambda/\lambda = (\Delta P/P)D^{-1}. \tag{1}$$

If we take the K_2^0 interaction length to be determined by the geometrical cross section of lead nuclei and use the results of Refs. 13 and 17 that the value of P changes by less than 10% between the two experiments, Eq. (1) tells us that λ cannot differ from the K_2^0 interaction length by more than 40%.

The conditions (i)-(iii) are necessary but not sufficient to prove the identity of L and K_2^0. Conclusive evidence against the CP-invariant explanations appears to come from measurements of the magnitude of the interference between LLD decays and regenerated $K_1^0 \to \pi^+\pi^-$ decays. If $L \equiv K_2^0$, the interfering amplitudes arise from the same source and the observed interference cannot depend on how the K_2^0's are produced. On the other hand, if L is distinct from K_2^0, the interference depends crucially on the relative phase of these two components, which we shall see depends strongly on the source of the kaon beam. To account for coherence between L and K_2^0 and simultaneously maintain CP invariance, we are obliged to identify L as a residue of the K_+ component which was coherently produced together with[18] $K_2^0 \equiv K_-$ in the original reaction which created the neutral kaon. Such a long-lived residue could arise through the mixing of K_+ with another state K_W, as described by Lipkin, or through some other cause, e.g., a radical change[19] from the exponential decay law for K_+ at some time $\tau < 12\tau_1$. Now, the relative phase of K_+ and K_- components is reversed when we replace a K^0 state

$$|K^0\rangle = 2^{-1/2}(|K_+\rangle + |K_-\rangle)$$

by

$$|\bar{K}^0\rangle = 2^{-1/2}(|K_+\rangle - |K_-\rangle).$$

Therefore, if a pure K^0 source is replaced by one exclusively producing $\bar{K}^0$'s, the interference term between LLD and regenerated $K_1^0 \to 2\pi$ decays must change sign in the CP-invariant theory.[20] In that case, if the kaons come from a source which provides an equal incoherent mixture of K^0's and $\bar{K}^0$'s, e.g., from $\bar{p}p$ annihilation under suitable conditions, the interference should disappear completely. For an arbitrary incoherent mixture of K^0's and $\bar{K}^0$'s, the interference term should be $\langle S\rangle$ times that for the pure K^0 case, where $\langle S\rangle$ is the average strangeness of the neutral-kaon beam at its origin. In the experiments reported in Ref. 14, the K^0 beam is expected to contain appreciable $\bar{K}^0$ contamination; therefore the CP-invariant theories would require a reduction of the interference effect from the maximum possible. Approximating the mean strangeness of the neutral kaons at their source by that of the charged kaons produced under similar circumstances[21] (found to be in the ratio $K^+:K^- \approx 3:1$[22]), CP-invariance would require the interference to be reduced by about one half. The experiments find[23,17] no indication of any reduction in the size of the interference effect, and certainly exclude any diminution by more than 10% in the amplitude of the interference term. To reconcile this result with the CP-invariant theory, K^0's would have to exceed $\bar{K}^0$'s in the ratio $K^0:\bar{K}^0 \geq 20:1$. This seems to rule out the model recounted in Ref. 1 together with most other CP-invariant theories of the LLD effect.[24]

The preceding discussion was predicated on the validity of the usual quantum theoretical description and the existence of a unique vacuum state. If the vacuum is taken to be a degenerate superposition of CP-even and CP-odd states,[25] any apparently CP-nonconserving amplitude can be reinterpreted as a CP-conserving one associated with a "CP flip" of the vacuum (in the usual jargon, with the emission of a CP spurion); therefore, such a description cannot be distinguished physically from the usual one with a unique vacuum, in which CP invariance is abandoned.[26] Finally, we consider the suggestion that the validity of quantum theory may be in question.[20] If so, it is necessary to find an alternative description before one can discuss the implications of long-lived 2π decays of neutral kaons. We note, however, that the usual theory, based on quantum mechanics, makes a clear-cut prediction of a CP-noninvariant effect.[3] Independent of any symmetry assumptions, it has been shown[27] that the K_1^0 and K_2^0 states differ very little from the components $K_\pm$, with well defined CP symmetry. Conversely, K^0 and $\bar{K}^0$ states are very close to being the linear superpositions $2^{-1/2}(K_1^0 \pm K_2^0)$, respectively. Thus the predictions that K_1^0-K_2^0 interference will be almost exactly reversed when we replace K^0 by $\bar{K}^0$ and that the time variation of K^0 and $\bar{K}^0$ decays into any self-conjugate channel will therefore be different rest only on the superposition principle and known properties of neutral kaons. *CP* invariance, on the other hand, would require that the time distribution of decays from an initial K^0 state to any state which transforms into itself under *CP* should be identical to the corresponding curve for an initial $\bar{K}^0$ state. The measurement of such a free decay curve has been reported for $\pi^+\pi^-$ decays from an almost pure K^0 beam.[21] If the experiment could be repeated with a $\bar{K}^0$ beam, or one in which the $\bar{K}^0/K^0$ ratio has been increased to the point where $\bar{K}^0$'s make a measurable contribution, one would know whether K_1^0-K_2^0 interference in $\pi^+\pi^-$ decays is the same for K^0 and $\bar{K}^0$ as required by *CP* invariance, or opposite as required by quantum theory.

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[1] H. J. Lipkin, Phys. Rev. Letters 22, 213 (1969); Cf. D. Lalović, ibid. 21, 1662 (1968).

[2] P. K. Kabir and R. R. Lewis, Phys. Rev. Letters 15, 306, 711, 908 (1965), where earlier references are given.

[3] A more expansive discussion can be found in P. K. Kabir, The *CP* Puzzle (Academic Press, Inc., New York, 1968).

[4] T. T. Wu and C. N. Yang, Phys. Rev. Letters 13, 380 (1964).

[5] We have tacitly assumed the validity of quantum mechanics and the existence of a unique vacuum state. The role of these assumptions will be discussed at the end of the paper.

[6] See, for example, R. F. Streater and A. S. Wightman, *CPT*, Spin-Statistics and All That (W. A. Benjamin, Inc., New York, 1964).

[7] J. Christenson, J. Cronin, V. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964); J.-M. Gaillard et al., ibid. 18, 20 (1967).

[8] A. Abashian and H. J. Lipkin, Phys. Letters 14, 151 (1965).

[9] G. B. Cvijanovich, E. A. Jeannet, and E. C. Sudarshan, Phys. Rev. Letters 14, 117 (1965).

[10] V. Fitch, R. Roth, J. Russ, and W. Vernon, Phys. Rev. Letters 15, 73 (1965).

[11] S. Bludman, Phys. Rev. 138, B213 (1965).

[12] J. Cronin, Argonne National Laboratory Report No. ANL 71-30, 1965 (unpublished).

[13] V. L. Fitch, R. Roth, J. Russ, and W. Vernon, Phys. Rev. 164, 1711 (1967).

[14] C. Alff-Steinberger et al., Phys. Letters 20, 207 (1966); M. Bott-Bodenhausen et al., ibid. 20, 212 (1966).

[15] E.g., J. Christenson et al., Phys. Rev. 140, B74 (1965).

[16] L. B. Okun and I. Ya. Pomeranchuk, Phys. Letters 16, 388 (1965).

[17] M. Bott-Bodenhausen et al., Phys. Letters 23, 277 (1966).

[18] The identification $K_2^0 \equiv K_-$ is made only to simplify the discussion; all that is necessary is that K_2^0 be coherent with K_-.

[19] L. A. Khalfin, Zh. Eksperim. i Teor. Fiz.–Pis'ma Redakt. 3, 129 (1966) [translation: JETP Letters 3, 81 (1966)].

[20] B. Laurent and M. Roos, Nuovo Cimento 40A, 788 (1965); M. Roos, Phys. Letters 20, 59 (1966).

[21] The validity of this procedure has recently been confirmed by A. Böhm et al., Phys. Letters 27B, 321 (1968).

[22] W. F. Baker et al., Phys. Rev. Letters 7, 101 (1961).

[23] C. Alff-Steinberger et al., Phys. Letters 21, 595 (1966).

[24] "In the foregoing discussion, we neglected the possible regeneration of K_1^0's from L, compared with regeneration from K_2^0, if $L \not\equiv K_2^0$. This is justified because measurements of K_1^0 regeneration agree quite well with the calculated regeneration from K_2^0's upon using experimental information on charged-kaon scattering."

[25] A. A. Grib, Zh. Eksperim. i Teor. Fiz.–Pis'ma Redakt. 2, 14 (1965) [translation: JETP Letters 2, 8 (1965)]; G. Marx, Phys. Rev. Letters 14, 334 (1965).

[26] A similar remark applies to the cosmological theory of Gürsey and Pais (unpublished) if experiments should turn out to be consistent with the superweak theory of L. Wolfenstein, Phys. Rev. Letters 13, 562 (1964).

[27] P. Eberhard, Phys. Rev. Letters 16, 150 (1966).