PHYSICS

A Possible Restriction on *CP*-Noninvariance in K°-Decay

THE generally accepted interpretation—which is the only remaining explanation within the framework of quantum mechanics—of the observed $K_2^\circ \rightarrow 2\pi$ decays[1,2] is that this is a manifestation of some CP-noninvariant interaction. Despite a large variety of suggestions as to the nature of the CP-noninvariant interaction, there has so far been no clear indication of CP-noninvariance in any other process and we still remain ignorant of the origin or nature of the interaction responsible for $K_2^\circ \rightarrow 2\pi$ decays. A phenomenological analysis of $K^\circ \rightarrow 2\pi$ decays has been given by Wu and Yang[3], but experiments carried out so far do not permit a unique determination of the relevant parameters. In the absence of a basic theory, it may be of interest to consider a simplifying assumption, which does not conflict with any known result, which fixes the parameters for $K_2^\circ \rightarrow 2\pi$ decay.

The condition which we wish to discuss is[4]

$$\langle K_1^\circ | K_2^\circ \rangle = 0 \qquad (1)$$

where K_1° and K_2° are the linear superpositions of K° and $\bar{K}^\circ$ states which are characterized by a purely exponential time-dependence in the Weisskopf–Wigner approximation. Assuming TCP-invariance, they are given by[5]

$$K_1^\circ = (1 + |r|^2)^{-1/2} (K^\circ + r\bar{K}^\circ) \qquad (2)$$
$$K_2^\circ = (1 + |r|^2)^{-1/2} (K^\circ - r\bar{K}^\circ)$$

where r is in general a complex constant determined by the dynamics of the $K^\circ - \bar{K}^\circ$ complex. From relations (2), we see that the condition (1) is equivalent to

$$|r|^2 = 1 \qquad (3)$$

From the disparity of K_1° and K_2° lifetimes, Lee, Oehme and Yang[5] could conclude that $|r|$ could not differ appreciably from unity. Taking $|m_2 - m_1| = 0{\cdot}5\ \tau_1^{-1}$, the restriction that an arbitrarily chosen neutral kaon beam can only decay with time yields the inequalities $0{\cdot}95 < |r| < 1{\cdot}05$. As is evident from (2), the phase of r depends on the choice of relative phase of K° and $\bar{K}^\circ$ states. We adopt the choice of Wu and Yang[3] which makes the amplitudes for K° and $\bar{K}^\circ$ to decay to the $I = 0$ $\pi\pi$ scattering eigenstate purely real. A limit on both the magnitude and phase of r can be obtained from a knowledge of the relative 2π decay rates of K_1° and K_2°. Using the formulae and notation of Wu and Yang, it can be shown quite generally that[6]

$$|(1 - r)/(1 + r)| \leqslant 2^{-1/2}\rho^{1/2}(2^{1/2}\rho^{1/2} - 1)^{-1}[2|\eta_{+-}| + 2^{1/2}\rho^{-1/2}|\eta_{00}|] \qquad (4)$$

where ρ is the branching ratio $\rho = \Gamma(K_1^\circ \rightarrow \pi^+\pi^-)/\Gamma(K_1^\circ \rightarrow \pi^\circ\pi^\circ)$. Even the rough limits which could be imposed on $|\eta_{00}|$ from knowledge of the K_2° lifetime and the partial rates for other decay modes beside $\pi^\circ\pi^\circ$ sufficed to determine that r is close to unity both in modulus—consistent with condition (3)—and phase (with the Wu–Yang phase convention). Recent measurements[2] of the $K_2^\circ \rightarrow \pi^\circ\pi^\circ$ rate, which yield $|\eta_{00}|$, reinforce the conclusion[7]. The condition (3) then requires that the small parameter $\varepsilon = 1 - r$ be purely imaginary,

$$Re\ \varepsilon = 0 \qquad (5)$$

If we assume, in accordance with the $\Delta I = \frac{1}{2}$ rule, that the $I = 2$ amplitudes are small compared with those for $I = 0$, we have the approximate relations[3]

$$\eta_{+-} = \tfrac{1}{2}[\varepsilon + \varepsilon'] \qquad (6a)$$
$$\eta_{00} = \tfrac{1}{2}[\varepsilon - 2\varepsilon'] \qquad (6b)$$

where ε' is a parameter describing the CP-violation in the $I = 2$ amplitude relative to the $I = 0$ amplitude. From relations (6a) and (6b), we see that relation (5) requires

$$Re\ \eta_{00} = -2\ Re\ \eta_{+-} = -2\ |\eta_{+-}| \cos \varphi_{+-} \qquad (7)$$

where φ_{+-} is the phase of η_{+-}. Equation (7) cannot be satisfied unless

$$|\eta_{00}| \geqslant 2\ |Re\ \eta_{+-}| = 2\ |\eta_{+-}|\ |\cos \varphi_{+-}| \qquad (8)$$

According to Rubbia and Steinberger[8], the best estimate for φ_{+-} is $\varphi_{+-} = 0{\cdot}60 \pm 0{\cdot}23$ radians. Equation (8) then requires

$$|\eta_{00}| \geqslant (3{\cdot}2 \pm 0{\cdot}6) \,.\, 10^{-3} \qquad (9)$$

using the value $|\eta_{+-}| = (1{\cdot}94 \pm 0{\cdot}09) \,.\, 10^{-3}$ quoted by Cronin *et al.*[2]. The condition (9) requires the presence of appreciable $I = 2$ amplitudes in $K_2^\circ \rightarrow 2\pi$ decay, because pure $I = 0$ would give $|\eta_{00}| = |\eta_{+-}|$. The likelihood that relation (3) could only be satisfied by an appreciable departure from the $\Delta I = \frac{1}{2}$ rule in $K_2^\circ \rightarrow 2\pi$ decay was previously noted by Bowen[4].

According to equation (7), for a given η_{+-}, the magnitude of η_{00} fixes its phase (within a two-fold ambiguity),

$$\cos \varphi_{00} = -2\ (Re\ \eta_{+-})/|\eta_{00}|$$
$$\varphi_{00} = \pi \pm \cos^{-1} [2\ (Re\ \eta_{+-})/|\eta_{00}|] \qquad (10)$$

A measurement of the phase of η_{00} is therefore of great interest as a test of the hypothesis (1). Taking the value of $|\eta_{00}|$ from Cronin *et al.*, $|\eta_{00}| = (4{\cdot}9 \pm 0{\cdot}5) \,.\, 10^{-3}$, we obtain the estimates,

$$\cos \varphi_{00} = -(0{\cdot}65 \pm 0{\cdot}20)$$
$$|\pi - \varphi_{00}| = 0{\cdot}86 \pm 0{\cdot}30 \text{ radians} \qquad (11)$$

The condition (1) has several other interesting consequences. The decay curve of any neutral kaon beam becomes simply the sum of two exponentials; furthermore, there is no charge-asymmetry in leptonic decays of K_2°, independent of the $\Delta S = \Delta Q$ rule[5]. If the $\Delta S = \Delta Q$ rule holds, the time dependent charge-asymmetry in leptonic decays from a beam which is initially pure K° is required to be exactly the opposite to that from a $\bar{K}^\circ$ beam. Also, the asymptotic decay rate into any particular channel becomes exactly the same whether we start with initial K° or $\bar{K}^\circ$ beams.

The significance of the restriction (1) is probably much deeper. Because such a condition scarcely occurs by accident, confirmation of hypothesis (1) would strongly suggest the existence of some hitherto unknown symmetry operation, of which K_1° and K_2° are distinct eigenstates. The possibility that there might be such a guiding principle beneath the apparent confusion created by the discovery of CP-nonconservation makes a test of the explicit prediction (10) extremely desirable.

I thank Prof. R. E. Peierls for a stimulating discussion.

P. K. KABIR

Rutherford High Energy Laboratory,
Chilton, Didcot, Berkshire.

Received January 18, revised February 6, 1967.

[1] Christenson, J. H., Cronin, J. W., Fitch, V. L., and Turlay, R., *Phys. Rev. Lett.*, **13**, 138 (1964).

[2] Gaillard, J-M., Krienen, F., Galbraith, W., Hussri, A., Jane, M. R., Lipman, N. H., Manning, G., Ratcliffe, T., Day, P., Parham, A. G., Payne, B. T., Sherwood, A. C., Faissner, H., and Reithler, H., *Phys. Rev. Lett.*, **18**, 20 (1967). Cronin, J. W., Kunz, P. F., Risk, W. S., and Wheeler, P. C., *Phys. Rev. Lett.*, **18**, 25 (1967).

[3] Wu, T. T., and Yang, C. N., *Phys. Rev. Lett.*, **13**, 380 (1964).

[4] Several interesting features of this condition, which we shall not discuss in this communication, have been noted by Patil, S. H., Tomozawa, Y., and Yao, Y-P., *Phys. Rev.*, **142**, 1041 (1966), by Bowen, T., *Phys. Rev. Lett.*, **16**, 112 (1966), and by Mathur, V. S., *Nuovo Cim.*, **44A**, 1268 (1966).

[5] Lee, T. D., Oehme, R., and Yang, C. N., *Phys. Rev.*, **106**, 340 (1957).

[6] The special case of equation (4) for the value $\rho = 2$ was previously quoted by Wolfenstein, L., *Nuovo Cim.*, **42**, 17 (1966).

[7] The strictest limit on the modulus, $0{\cdot}99 \leqslant |r|^2 \leqslant 1{\cdot}01$, is obtained from the unitarity condition stated by Bell, J. S., and Steinberger, J., *Proc. Oxford Intern. Conf. on Elementary Particles, Rutherford Laboratory*, 1966.

[8] Rubbia, C., and Steinberger, J., *Phys. Lett.*, **23**, 167 (1966).

Characteristics of Fibre Friction

AMONTONS's classical law of friction, as explained by the cohesion theory, accounts satisfactorily for most cases of metallic friction. For non-metallic materials, however, and in particular the elastic solid field of polymeric monofilaments and natural fibrous materials, many exceptions