



CM-P00056959

CP INVARIANCE AND THE 2π DECAY MODE OF THE K_2^0 *)

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*) Work supported in part by the U.S. Atomic Energy Commission, the Army Research Office (Durham) and the National Science Foundation.

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In a recent experiment Christenson, Cronin, Fitch and Turlay ¹⁾ have found definite indications that the long lived component of the K^0 , the K_2^0 , decays into two π mesons

$$K_2^0 \rightarrow 2 \pi \quad (1)$$

The most direct interpretation of their experiment is to assume that CP invariance is violated ²⁾ in this decay and hence in the weak interactions in general. However, it is important to realize that this experiment involves an entirely new domain of phenomena, those involving extremely small energies. The experiment of Christenson et al. is capable of detecting energy differences of the order of 10^{-8} eV. No other experiment in particle physics, up to now, has exhibited such sensitivity to small energies. On the other hand, none of the other experiments ³⁾ on weak interactions that might have shown CP violation has done so. Therefore it is not unnatural to try to explain the new experiments in some other way. In this note we shall attempt to reconcile the two assumptions :

- i) CP invariance holds for all interactions:
- ii) the long lived component of the K^0 , in (local) vacuum, or at least in what is usually called "vacuum", decays into 2π 's.

Up to now vacuum in particle physics has been taken to mean the absence of neighbouring material objects, although not necessarily that of long range fields such as gravitational or electromagnetic fields. These conventional fields, which are produced by distant bodies such as Milky Way and the other galaxies, are sufficiently well understood so that one can assume, with some confidence, that their effects on the K^0, \bar{K}^0 system can be neglected, either because they are too small (we have in mind the possible electromagnetic conversion between K_1^0 and K_2^0 due to the difference in the charge radius of K^0 and \bar{K}^0) or because they have the same effect on particles and antiparticles (e.g., gravitational forces).

In this note we hypothesize that there is a new long range, extremely weak, field which can be neglected so long as one does not measure energies as small as those measured in the experiment of Christenson et al. This field, we assume, produces a potential energy which is equal in magnitude and opposite in sign for K^0 and \bar{K}^0 , say $(\frac{1}{2})V$ for K^0 but $-(\frac{1}{2})V$ for \bar{K}^0 . This new interaction is CP conserving and if we could maintain a given K^0 and \bar{K}^0 system, but transform the environment into its CP conjugate state, then this potential energy would reverse sign⁴⁾.

As we shall see, this possibility leads to unique predictions concerning other "apparent" CP violating results which are in general quite different from the alternative possibility²⁾ of assuming CP non-invariance of weak interactions. Our analysis does not depend on the precise nature of the new interaction except that it must produce a potential energy difference V between K^0 and \bar{K}^0 . [To give an example, we may envisage that this potential energy difference is transmitted by a four-vector field similar to the electromagnetic interaction. It can be generated by any strongly interacting particle and has an amplitude proportional to, say, I_z , or $\frac{1}{2}(N+S)$, of the particle where I_z = z component of isotopic spin and N = baryon number, S = strangeness. (We leave open the question of whether it can have leptonic couplings.)]

Whatever the origin of this interaction with macroscopic bodies, the fact that it gives rise only to a static potential energy implies that so far as energies of the order of 10^{-8} eV can be neglected in the decays of all particles other than neutral K mesons, there are no observable "apparent" CP non-invariant effects. For the neutral K meson, all other "apparent" CP non-invariant effects are completely determined by the parameter V .

We first discuss the problem of a K meson in local isolation (i.e., in the absence of any neighbouring matter but taking into account the effects of the new long range interaction with distant objects). Let $\psi(t)$ be the wave function of a K meson in the laboratory system.

In what follows, we regard t as the independent variable and the co-ordinate \underline{r} of the K meson as a dependent variable given by $(\underline{r}_0 + \underline{v}t)$ where \underline{v} is the K meson velocity and \underline{r}_0 is its initial co-ordinate. The relative velocity of the laboratory and the distant macroscopic bodies will be neglected compared to the velocity of the K in the laboratory. We may write :

$$\psi(t) = a(t) |K^0\rangle + b(t) |\bar{K}^0\rangle, \quad (2)$$

or simply

$$\psi(t) = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \quad (3)$$

where

$$|\bar{K}^0\rangle \equiv CP |K^0\rangle. \quad (4)$$

The time development of $\psi(t)$ can be determined from

$$i \frac{d\psi}{dt} = (\eta + \xi \sigma_x + \zeta \sigma_z) \psi \quad (5)$$

where

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad (6)$$

and, for a locally isolated system, η , ξ , ζ , are given by ($\hbar=c=1$)

$$\eta = \eta_0 = \frac{1}{2\gamma} \left[(m_1 + m_2) - i \frac{1}{2} (\Gamma_1 + \Gamma_2) \right], \quad (7)$$

$$\xi = \xi_0 = \frac{1}{2\gamma} \left[(m_1 - m_2) - i \frac{1}{2} (\Gamma_1 - \Gamma_2) \right] \quad (8)$$

4.

and

$$\xi = \xi_0 = \frac{1}{2} V \quad (9)$$

The subscript 0 indicates that these are values for the K meson in a locally isolated system, and

$$\gamma = (1 - v^2)^{-\frac{1}{2}} \quad (10)$$

where v = velocity of the K meson in the laboratory. In the above equations, $\xi_0 \sigma_z$ is the effect of the new interaction, m_1, Γ_1 and m_2, Γ_2 are the mass and width of K_1^0 and K_2^0 if $V=0$. The solution of Eq. (5) is well known. There are two eigensolutions $\Psi_1(t)$ and $\Psi_2(t)$ which are given by

$$\Psi_1 = (1 + |\epsilon|^2)^{-\frac{1}{2}} [\psi_+ + \epsilon \psi_-] e^{-i\lambda_1 t}$$

and

$$\Psi_2 = (1 + |\epsilon|^2)^{-\frac{1}{2}} [\psi_- - \epsilon \psi_+] e^{-i\lambda_2 t} \quad (11)$$

where

$$\psi_{\pm} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm 1 \end{pmatrix}, \quad (12)$$

$$\epsilon = \xi^{-1} \left[-\xi + (\xi^2 + \xi^2)^{\frac{1}{2}} \right], \quad (13)$$

$$\lambda_1 = \eta + (\xi^2 + \xi^2)^{\frac{1}{2}} \quad (14)$$

and

$$\lambda_2 = \eta - (\xi^2 + \xi^2)^{\frac{1}{2}} \quad (15)$$

Using Eqs. (7)-(9) and assuming small V , we find

$$\epsilon = \epsilon_0 \cong \frac{1}{2} \gamma V \left[(m_1 - m_2) - i \frac{1}{2} (\Gamma_1 - \Gamma_2) \right]^{-1}$$

The value ϵ_0 for the experiment of Christenson et al., is found to be

$$|\epsilon_0| \cong 2 \times 10^{-3} \quad (16)$$

It is important to note that if V is due to the average of the fourth component of a vector field, then V is independent of the energy of the K meson. Thus the parameter ϵ_0 depends linearly on γ . [On the other hand, V is proportional to γ^{-1} if it is due to a spin 0 field, and is proportional to γ if it is due to a spin 2 field. However, in the framework of a simple local field theory, both spin 0 and spin 2 fields give equal static potential for a particle and its antiparticle. Therefore it seems more attractive to assume that this new interaction is due to a vector field with an extremely small mass.]

The solution, Eq. (11), also determines other "apparent" CP non-invariant effects in the K decay. For example, the ratio

$$r_i \equiv \frac{\text{rate}(K_i^0 \rightarrow \pi^- + \ell^+ + \nu_\ell)}{\text{rate}(K_i^0 \rightarrow \pi^+ + \ell^- + \bar{\nu}_\ell)}$$

can be different from 1, where $i=1$ or 2 , and $\ell = e$ or μ . Assuming that the $\Delta Q = \Delta S$ rule holds, we find

$$r_1 = \left| \frac{1 + \epsilon_0}{1 - \epsilon_0} \right|^2$$

and

$$r_2 = \left| \frac{1 - \epsilon_0}{1 + \epsilon_0} \right|^2 \quad (17)$$

which gives $|r_1 - 1| \simeq 6 \times 10^{-3}$ for the ϵ_0 given by Eq. (16).

Next, we discuss the problem of a K meson in a medium. Let n and n' denote, respectively, the complex indices of refraction of K^0 and \bar{K}^0 in the medium⁵⁾. Eq. (5) remains valid where, instead of Eqs. (7)-(9), the parameters η , ξ , ζ are now given by

$$\eta = \frac{1}{2\gamma} \left[(m_1 + m_2) - i \frac{1}{2} (\Gamma_1 + \Gamma_2) \right] - \frac{1}{2} (n + n') k v, \quad (18)$$

$$\xi = \frac{1}{2\gamma} \left[(m_1 - m_2) - i \frac{1}{2} (\Gamma_1 - \Gamma_2) \right], \quad (19)$$

$$\zeta = \frac{1}{2} \left[V - (n - n') k v \right] \quad (20)$$

and k is the momentum of the K meson.

The solution, Eq. (11), also remains valid. For $|\zeta| \ll |\xi|$, the parameter ϵ is given approximately by

$$\epsilon \simeq \frac{1}{2} \gamma \left[V - (n - n') k v \right] \left[(m_1 - m_2) - i \frac{1}{2} (\Gamma_1 - \Gamma_2) \right]^{-1} \quad (21)$$

The absolute magnitude of ϵ in a medium can be obtained by measuring the corresponding rate of reaction (1). The interference term between V and $(n - n') k v$ in the expression for $|\epsilon|$ can also determine the sign of V .

It is interesting to speculate on the possible nature of such a long range interaction. As mentioned in the preceding discussion, a simple possibility is to make the ad hoc assumption of the existence of

a four-vector field which interacts with all particles. For definiteness, let us assume that the effective "charge" for all strongly interacting particles is

$$f \times I_3 \quad (22)$$

or $f \times \frac{1}{2}(N+S)$, where f is a dimensionless coupling constant. The potential energy difference V between K^0 and \bar{K}^0 due to the Milky Way is simply given by ⁶⁾

$$V \sim \frac{f^2}{2} \left(\frac{M_g}{m_p} \right) \frac{1}{R} \quad (23)$$

where M_g = mass of the galaxy, m_p = mass of proton, and R = effective radius of the galaxy, defined so that $GM_g R^{-1}$ = gravitational potential on earth due to the galaxy, G is the gravitation constant. The factor $\frac{1}{2}$ is due to the isospin value of p . It seems reasonable to assume that effects from very distant galaxies are small, and the main contribution is due only to the Milky Way. By taking $M_g \sim 10^{11}$ \times solar mass, $R \sim 10$ kpc and $V \sim 5 \times 10^{-4}$ cm^{-1} , we find

$$f^2 \sim 2.5 \times 10^{-49} \quad (24)$$

Such a long range force would also give rise to a slight difference between the observed "gravitational" mass and inertial mass ⁷⁾. The current experimental upper limit ⁸⁾ on f^2 is

$$f^2 < \sim 2 \times 10^{-45} \quad (25)$$

which is certainly compatible with Eq. (24).

Two of us (JB and TDL) wish to thank Dr. S.F. Tuan for discussions, and Professors V.F. Weisskopf and L. Van Hove for the hospitality extended to us at CERN.

R E F E R E N C E S

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