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CP VIOLATION IN $K^0(\bar{K}^0) \rightarrow 2\gamma$ DECAY

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A B S T R A C T

With the newly available intense $K^0(\bar{K}^0)$ beams of the low energy antiproton ring (LEAR) at CERN, measurements of CP violation in channels other than $K \rightarrow \pi\pi$ are possible. We study CP violation in the $K^0(\bar{K}^0) \rightarrow 2\gamma$ decay.

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1. INTRODUCTION

The decay of the long-lived K meson K_L into two pions is so far the only clear evidence for CP violation. It is difficult to measure CP violation in other decay channels because either it does not correspond to a simple violation of a selection rule as in $K_L \rightarrow \pi\pi$ or the corresponding branching ratios are extremely small [e.g. $B(K_S \rightarrow 3\pi) < 10^{-8}$]. In any case the following theorem by Sehgal and Wolfenstein [1] forms the basis for identifying CP violation in other decays than into two pions: "For any possible non-leptonic decay mode of the K^0 meson, the observation of an interference effect between K_L and K_S decays in the partial decay rates is clear evidence of CP violation". The most feasible way of detecting interference effects [2] seems to be to measure the asymmetry of the decay intensities using a beam of $\bar{K}^0$ particles as well as a beam of K^0 particles.

By using the high-intensity antiproton source of LEAR, it is possible to produce well-defined sources of K^0 and $\bar{K}^0$ through the reactions:

In these reactions the strangeness of the neutral beam can be uniquely identified through the detection of the companion K^+ and K^- . The possibility of tagging K^0 's and $\bar{K}^0$'s separately with a flux such as the one provided by LEAR is unique and is almost inconceivable at external beams.

In this paper we concentrate on the $K \rightarrow 2\gamma$ channel. The most feasible and most accurate of the experimental methods seems to be to measure the (time-dependent) asymmetry $\Delta(t)$ of intensities between K^0 and $\bar{K}^0$ beams

$$\Delta(t) = \frac{I(K^0 \rightarrow 2\gamma) - I(\bar{K}^0 \rightarrow 2\gamma)}{I(K^0 \rightarrow 2\gamma) + I(\bar{K}^0 \rightarrow 2\gamma)} = I^{\gamma\gamma}(t).
 \tag{2}$$

In our opinion $K \rightarrow 2\gamma$ is very well suited for such a study because firstly by involving electromagnetism it does not obey isospin invariance (barrier effects), and secondly the measurement of the $K_S \rightarrow 2\gamma$ branching ratio, which is at present unknown, will check our understanding of neutral kaon decays. Furthermore, as was shown [1, 3] a long time ago it is always non-vanishing (and of order ϵ) because of CP violation in the $K-\bar{K}^0$ mass matrix. Here we study the implications of CP violation in both the mass matrix and the decay amplitudes. The decay amplitudes are the sum of the short- and long-distance contributions. To compute the short-distance contributions the Weinberg-Salam (WS) model [4] is used and some remarks on the predictions of other models are made. Long-distance effects are described by using the 2π and 3π intermediate states (neglecting $2\pi\gamma$). We conclude that in the actual scheme of the Kobayashi-Maskawa (KM) model, CP violation in the $K \rightarrow 2\gamma$ decay amplitudes is extremely difficult to measure. Our conclusion holds true also in other models of CP violation which are still not ruled out.

2. $K \rightarrow 2\gamma$

We adopt the usual convention which relates the eigenstates of strangeness, $|K^0\rangle$ and $|\bar{K}^0\rangle$, as

$$\text{CP } |K^0\rangle = -|\bar{K}^0\rangle. \quad (3)$$

The particles K_S and K_L are then given as

$$\begin{aligned} |K_S\rangle &= (1/\sqrt{2}) (1+\epsilon^2)^{\frac{1}{2}} \{ (1+\epsilon)|K^0\rangle - (1-\epsilon)|\bar{K}^0\rangle \} \\ |K_L\rangle &= (1/\sqrt{2}) (1+\epsilon^2)^{\frac{1}{2}} \{ (1+\epsilon)|K^0\rangle + (1-\epsilon)|\bar{K}^0\rangle \}. \end{aligned} \quad (4)$$

For the transitions from K^0 or $\bar{K}^0$ to a system of two photons, there exist two possible states for the photon pair: $2\gamma(+)$ ($\equiv F_{\mu\nu} F^{\mu\nu}$) with CP = +1 and $2\gamma(-)$ ($\equiv \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta}$) with CP = -1. Following the parametrization of ref. [3] we denote the various $K \rightarrow 2\gamma$ decay amplitudes as follows:

$$\begin{aligned} A(+) &\equiv A[K^0 \rightarrow 2\gamma(+)] , & \bar{A}(+) &\equiv A[\bar{K}^0 \rightarrow 2\gamma(+)] \\ A(-) &\equiv A[K^0 \rightarrow 2\gamma(-)] , & \bar{A}(-) &\equiv A[\bar{K}^0 \rightarrow 2\gamma(-)] , \end{aligned} \quad (5)$$

or referring to the K_S and K_L states

$$\begin{aligned} A_S(+) &\equiv A[K_S \rightarrow 2\gamma(+)] , & A_S(-) &\equiv A[K_S \rightarrow 2\gamma(-)] \\ A_L(+) &\equiv A[K_L \rightarrow 2\gamma(+)] , & A_L(-) &\equiv A[K_L \rightarrow 2\gamma(-)] . \end{aligned} \quad (6)$$

We have then four independent amplitudes $A(+)$, $\bar{A}(+)$, $A(-)$, and $\bar{A}(-)$ and it is convenient to define the following relative ratios:

$$\frac{A(+)}{\bar{A}(+)} = -r_1 e^{i\phi_1} , \quad \frac{A(-)}{\bar{A}(-)} = r_2 e^{i\phi_2} , \quad \frac{\bar{A}(-)}{\bar{A}(+)} = i r e^{i\phi} , \quad (7)$$

where r_1 , r_2 , and r are real and positive. In a CP-invariant world

$$r_1 = r_2 = 1 , \quad \phi_1 = \phi_2 = 0 \quad (8)$$

since $A(+) = -\bar{A}(+)$ and $A(-) = \bar{A}(-)$.

Alternatively, we can parametrize the amplitudes in eqs. (3) and (4) by three complex numbers ϵ_1 , ϵ_2 , and λ

$$\epsilon_1 = \frac{A_L(+)}{A_S(+)} , \quad \epsilon_2 = \frac{A_S(-)}{A_L(-)} , \quad \lambda = \frac{A_L(-)}{A_S(+)} . \quad (9)$$

The relation between the two sets of parameters defined in eqs. (7) and (9) is:

$$\begin{aligned} \epsilon_1 &= \frac{r_1 e^{i\phi_1} - (1-\epsilon)/(1+\epsilon)}{r_1 e^{i\phi_1} + (1-\epsilon)/(1+\epsilon)} \\ \epsilon_2 &= \frac{r_2 e^{i\phi_2} - (1-\epsilon)/(1+\epsilon)}{r_2 e^{i\phi_2} + (1-\epsilon)/(1+\epsilon)} \\ \lambda &= -i r e^{i\phi} \frac{r_2 e^{i\phi_2} + (1-\epsilon)/(1+\epsilon)}{r_1 e^{i\phi_1} + (1-\epsilon)/(1+\epsilon)} . \end{aligned} \quad (10)$$

The total decay rates $K_S \rightarrow 2\gamma$ and $K_L \rightarrow 2\gamma$, expressed in terms of the parameters introduced in eqs. (6) and (9), are

$$\begin{aligned}\Gamma_S (K_S \rightarrow 2\gamma) &= \frac{1}{32\pi m_S} \{ |A_S(+)|^2 (1 + |\epsilon_2|^2 |\lambda|^2) \\ \Gamma_L (K_L \rightarrow 2\gamma) &= \frac{1}{32\pi m_L} \{ |A_S(+)|^2 (|\lambda|^2 + |\epsilon_1|^2) ,\end{aligned}\quad (11)$$

where m_S and m_L are the physical masses of K_S and K_L , respectively.

By defining a ratio R as

$$R \equiv \frac{\Gamma_S(2\gamma)}{\Gamma_L(2\gamma)} , \quad (12)$$

eq. (11) gives the following constraints on ϵ_1 and ϵ_2

$$|\epsilon_1|^2 \geq \frac{1}{R} \quad \text{and} \quad |\epsilon_2|^2 \geq R \quad (13)$$

or

$$|\epsilon_1|^2 \leq \frac{1}{R} \quad \text{and} \quad |\epsilon_2|^2 \leq R . \quad (14)$$

According to the definition of the K^0 and $\bar{K}^0$ states as

$$\begin{aligned}|K^0\rangle &= \frac{(1 + |\epsilon|^2)^{\frac{1}{2}}}{\sqrt{2}(1 + \epsilon)} \{ |K_S\rangle + |K_L\rangle \} \\ |\bar{K}^0\rangle &= \frac{(1 + |\epsilon|^2)^{\frac{1}{2}}}{\sqrt{2}(1 - \epsilon)} \{ |K_L\rangle - |K_S\rangle \} .\end{aligned}\quad (15)$$

It is easy to see that the total intensities $I(t)$ ($K^0 \rightarrow 2\gamma$) and $I(t)$ ($\bar{K}^0 \rightarrow 2\gamma$) are given by

$$\begin{aligned}I(t) (K^0 \rightarrow 2\gamma) &= \frac{1 + |\epsilon|^2}{2(1 + 2 \operatorname{Re} \epsilon + |\epsilon|^2)} \{X(t) + Y(t)\} \\ I(t) (\bar{K}^0 \rightarrow 2\gamma) &= \frac{1 + |\epsilon|^2}{2(1 - 2 \operatorname{Re} \epsilon + |\epsilon|^2)} \{X(t) - Y(t)\}\end{aligned}\quad (16)$$

where

$$\begin{aligned}X(t) &= \{ [|A_L(-)|^2 + |\epsilon_1|^2 |A_S(+)|^2] e^{-\Gamma_L t} + [|A_S(+)|^2 + |\epsilon_2|^2 |A_L(-)|^2] e^{-\Gamma_S t} \} \\ Y(t) &= \{ [2|\epsilon_1|^2 |A_S(+)|^2 \cos(\theta_1 - \Delta m t) + 2|\epsilon_2|^2 |A_L(-)|^2 \cos(\theta_2 + \Delta m t)] e^{-(\Gamma_L + \Gamma_S)t} \}\end{aligned}\quad (17)$$

and by neglecting terms of order $|\epsilon|^2$ we obtain*)

*) The difference between eq. (18) and the corresponding one given in ref. [3] is due to the wrong normalization of the K^0 and $\bar{K}^0$ -states in ref. [3].

$$A(t) = \frac{Y(t) - 2 \operatorname{Re}(\epsilon) X(t)}{X(t) - 2 \operatorname{Re}(\epsilon) Y(t)} . \quad (18)$$

Before closing this section, we would like to stress the special case of the superweak models, where we obtain

$$\epsilon_1 = \epsilon_2 = \epsilon . \quad (19)$$

With the present measured value of ϵ we derive a bound

$$R \leq 1/|\epsilon|^2 \approx 2.5 \times 10^5 . \quad (20)$$

3. SHORT-DISTANCE BEHAVIOUR

Let us examine here the CP violation in the $K \rightarrow 2\gamma$ decay amplitudes assuming the KM model to be the source of CP violation. Doing so we have to perform first a redefinition [5] of K^0 and $\bar{K}^0$ states in order to obtain a real amplitude for the decay $K \rightarrow \pi\pi$ in the $I = 0$ channel. We recall that the "Penguin" Hamiltonian introduces in the total decay amplitude of $K^0 \rightarrow 2\pi$ ($I = 0$) a phase ξ so that the amplitude becomes, apart from final-state $\pi\pi$ strong interactions,

$$A_{0,\text{real}} e^{i\xi} , \quad (21)$$

where [5]

$$\xi \approx s_2 c_2 s_3 \sin \delta \frac{\ln(m_c^2/m_t^2)}{\ln(m_c^2/m^2) - s_2^2 \ln(m_c^2/m_t^2)} \leq O(10^{-3}) \quad (22)$$

and s_2 , c_2 , s_3 , and $\sin \delta$ refer to the KM matrix [6]. By redefining

$$|K^0\rangle \rightarrow e^{-i\xi} |K^0\rangle \quad (23)$$

$$|\bar{K}^0\rangle \rightarrow e^{i\xi} |\bar{K}^0\rangle$$

the amplitude [eq. (21)] becomes real, so that we have the standard convention, while ϵ becomes

$$\varepsilon = 1/\sqrt{2} |\varepsilon_m + \xi| e^{i\pi/4}, \quad (24)$$

with

$$\varepsilon_m = \frac{1}{2} \left(\frac{\text{Im } M_{12}}{\text{Re } M_{12}} \right). \quad (25)$$

The ratios of amplitudes in eq. (7), which are relevant to our subsequent discussion, transform according to

$$\frac{A(+)}{\bar{A}(+)} \rightarrow \frac{A'(+)}{\bar{A}'(+)} = \frac{A(+)}{\bar{A}(+)} e^{-2i\xi} = -r_1 e^{i(\phi_1 - 2\xi)} \quad (26)$$

$$\frac{A(-)}{\bar{A}(-)} \rightarrow \frac{A'(-)}{\bar{A}'(-)} = \frac{A(-)}{\bar{A}(-)} e^{-2i\xi} = r_2 e^{i(\phi_2 - 2\xi)}. \quad (27)$$

Now we turn to the discussion of the short-distance contributions to the decay of $K^0(\bar{K}^0) \rightarrow 2\gamma$. A long time ago Gaillard and Lee [7], assuming $m_q \ll \mu_W$, showed that only the diagram in fig. 1 contributes to leading order in $1/\mu_W^2$. Working in an expansion in $1/\mu_W^2$ and using a Fierz transform the diagram of fig. 1 is equivalent to fig. 2, which corresponds to the decay of the π^0 , i.e. it is proportional to $\varepsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta}$, representing thus a $\gamma\gamma(-)$ state.

Furthermore, using PCAC to relate the axial current to the kaon:

$$\langle 0 | J_\mu | K_L \rangle = i \frac{1}{\sqrt{2}} f_K (p_K)_\mu, \quad (28)$$

we obtain

$$iA [K^0 \rightarrow \gamma\gamma(-)] = iF_{\mu\nu} \tilde{F}^{\mu\nu} Gf \frac{8\alpha}{9\pi} f_K \sum_i U_{sj}^* U_{dj} A_j \left(\frac{m_q^2}{m_K^2} \right),$$

where A_j is a function of the quark masses used in ref. [7]. For $(m_q/m_K)^2 > 3$ we obtain $A_j < 0.005$, which in turn means that the only sizeable contribution is due to the u-quark. This means that

$$\frac{A'(-)}{\bar{A}'(-)} = 1 \quad (29)$$

because $(\bar{u}d)$ and $(\bar{u}s)$ couplings are real. From eq. (27) we then obtain

$$r_2 = 1, \quad \phi_2 = +2\xi, \quad (30)$$

neglecting all other contributions in $K^0 \rightarrow \gamma\gamma(-)$. This contribution explains already a large fraction of the $K_L \rightarrow 2\gamma$ decay since

$$\frac{\Gamma(K_L \rightarrow 2\gamma)}{\Gamma_{\text{meas}}(K_L \rightarrow 2\gamma)} \simeq 60\%. \quad (31)$$

All other diagrams, including the non-dominant part of fig. 1, give short-distance contributions to $K \rightarrow 2\gamma(+)$. However, an inspection of these diagrams shows that they are suppressed by the order of $m_q^2 \times \text{mixing angles}/\mu_w^2$. A crude estimate shows that the ratio of the amplitudes of $K \rightarrow \gamma\gamma(+)$ to $K \rightarrow \gamma\gamma(-)$ coming from short-distance contributions is of the order of 10^{-4} and we neglect thus these contributions in our numerical estimates.

4. OTHER CONTRIBUTIONS

i) Decay into $\gamma\gamma(+)$: The dominant decay mode into $\gamma\gamma(+)$ is due to the 2π intermediate state. All other contributions are suppressed at least by a factor of α_{em} , i.e. they are negligible [3]. Moreover, using the experimental fact that $A[K^0 \rightarrow 2\pi (I=0)]/A[K^0 \rightarrow 2\pi (I=2)] = 1/20$, we arrive at the approximation

$$\frac{A'(+)}{\bar{A}(+)} \simeq \frac{A[K^0 \rightarrow 2\pi (I=0)] A(2\pi \rightarrow \gamma\gamma)}{A[\bar{K}^0 \rightarrow 2\pi (I=0)] A(2\pi \rightarrow \gamma\gamma)} \quad (32)$$

and, since $A(2\pi \rightarrow \gamma\gamma)$ is CP-invariant, eq. (32) becomes

$$\frac{A'(+)}{\bar{A}'(+)} = \frac{A[K^0 \rightarrow 2\pi (I=0)]}{A[\bar{K}^0 \rightarrow 2\pi (I=0)]} = -e^{2i\xi}. \quad (33)$$

Using again the dominance of the "penguin" Hamiltonian [4] we find

$$r_1 = 1, \quad \phi_1 = 0. \quad (34)$$

ii) Decay into $\gamma\gamma(-)$: Apart from the short-distance contribution, the 3π intermediate state can also contribute. The 3π is either in the $I = 1$ or 3 state, possibly with equal amplitudes. If there exists a violation of CP in K^0 or $\bar{K}^0$ into 3π decay and if the amplitudes involving short-distance contributions and 3π are comparable, then we could obtain a drastic change in eq. (27). Experimentally the violation of CP in the $K \rightarrow 3\pi$ channel is not well known. However, some time ago Li and Wolfenstein [8] calculated η_{+-0} in the KM model using PCAC. They found

$$|\eta_{+-0} - \eta_{+--}| < 0.06 |\epsilon| . \quad (35)$$

Using this constraint we are able to show that CP violation in the $K \rightarrow 3\pi$ amplitudes gives a very small correction to $A(-)/\bar{A}(-)$. Indeed, if $\eta_{+-0} = \epsilon$, the amplitudes $\langle 3\pi | H_W | K^0 \rangle$ and $\langle 3\pi | H_W | \bar{K}^0 \rangle$ are equal and real. From the small possible deviations of η_{+-0} from ϵ we expect small changes in r_2 and ϕ_2 . Recently another contribution to the short-distance effects coming from the η' intermediate state has been discussed [9]. This contribution gives the following change in ϕ_2

$$\phi_2 \rightarrow \phi_2 + 2\xi(1+x) , \quad (36)$$

where x is the ratio of the total long-range over the short-range contribution to the $A(-)$ amplitude and it can be at most a few tens of a per cent.

Before closing this section we note that the results obtained so far for the short-distance contributions to $K \rightarrow 2\gamma$ in the KM model remain unchanged in other models of CP violation (left-right [10], Higgs [11], horizontal [12]).

In the left-right (L-R) symmetric models the structure of the diagrams is changed whenever a left-handed and a right-handed boson act together. However, the L-R mixing angle is very small [13] ($\tan \alpha \leq 0.005$) and therefore the change in the diagrams is completely negligible. We have also checked that the neutral flavour-changing Higgs in the L-R models gives a negligible contribution. Models with a richer Higgs structure [11] than the WS model also give extremely small contributions. Because of their flavour-changing neutral currents, they have to

be heavy and then the large mass in the propagator makes the change negligible. Finally, in the horizontal models the change in the structure of the diagrams is negligible again because of the heaviness of the carriers of the horizontal interactions [14].

5. NUMERICAL RESULTS AND CONCLUSIONS

Our numerical analysis shows that $\Delta(t)$ is very sensitive to the value of R [see eq. (12)], which is at present unknown. We present results for two values of R , i.e. 10 and 500, the latter being the bound allowed from the experimental upper bound of the $K_S \rightarrow 2\gamma$ branching ratio (see fig. 3).

If we neglect the $K \rightarrow 3\pi$ amplitude the situation is the following. The short-distance contribution explains completely the decay into the $2\gamma(-)$ state. In this approximation the only CP violation in the decay amplitude is due to ξ . Numerical calculations show that the experiment will not be sensitive to the parameter ξ , even if $\xi \approx 10^{-2}$. Therefore, the asymmetry $\Delta(t)$ is indistinguishable from the superweak model (see fig. 3). If the 3π intermediate state has a contribution comparable to that of the short distance and if, in contradiction to the theoretical prediction, η_{+-0} is very different from ϵ , then a measurable effect could be seen in $\Delta(t)$.

Similarly, if the η' contribution is much more sizeable than it is estimated, it could also lead to a measurable effect in $\Delta(t)$. For completeness we present for comparison in fig. 4 results for different values of ϕ_2 assuming as an example $r_2 = 0.9$. Here in order to achieve the maximum sensitivity we use the asymmetry of the integral rates [2], defined as

$$I^{\gamma\gamma} = \frac{\int_0^{20\tau_S} R(\bar{K}^0 \rightarrow 2\gamma) dt - \int_0^{20\tau_S} R(K^0 \rightarrow 2\gamma) dt}{\int_0^{20\tau_S} R(\bar{K}^0 \rightarrow 2\gamma) dt + \int_0^{20\tau_S} R(K^0 \rightarrow 2\gamma) dt} \quad (37)$$

Taking into account the new experimental situation with the intense beams of tagged K^0 's and $\bar{K}^0$'s at LEAR, we conclude in the framework of present theories

that by measuring $K^0(\bar{K}^0) \rightarrow 2\gamma$ it will only be possible to verify firstly that CP is indeed violated in this channel, but without the possibility of distinguishing milliweak from superweak predictions. Secondly, the branching ratio of $K_S \rightarrow 2\gamma$ can be extracted and finally a bound on new types of CP violation can be achieved.

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Figure captions

- Fig. 1 Dominant short-distance contribution to $K \rightarrow 2\gamma$.
- Fig. 2 The diagram to which the diagram of fig. 1 is reduced in leading order
 in μ_W^{-2} .
- Fig. 3 Calculated asymmetry for the superweak model using two values for R.
- Fig. 4 Asymmetry in the KM (WS) model assuming strong CP violation in the
 amplitude.

Fig. 1

Fig. 2

Fig. 3a

Fig. 3b

Fig. 4