Decay $\phi \to K^0\bar{K}^0\gamma$ and Its Possible Effects on Future Kaon Factories

S. Nussinov[(a)] and Tran N. Truong[(b)]
Department of Physics, University of California, Los Angeles, Los Angeles, California 90024-1597
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The branching ratio of $\phi \to K^0\bar{K}^0\gamma$ is calculated to be 10^{-5}–10^{-6}. Because of the soft photon involved, this decay could be an important background in future $K^0\bar{K}^0$ factories.

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The process $e^+e^- \to$ "γ" $\to K^0\bar{K}^0 (=K_LK_S)$ is an attractive source of correlated $K^0\bar{K}^0$ pairs. Assuming charge conjugation C is conserved in strong and electromagnetic interactions, the $K^0\bar{K}^0$ state in ϕ decay (C odd) is purely K_LK_S. Thus special-purpose "kaon factories" at the ϕ^0 mass are considered as means for precision measurements of the CP-violating parameter in the $K^0\bar{K}^0$ complex and for finding bounds on CPT violation.[1] Such efforts requires understanding if the C-even backgrounds due to production of $K^0\bar{K}^0$ in S wave (or higher even partial wave) is substantial.

There are two types of background: the intrinsic one where the $K^0\bar{K}^0$ pairs in the even partial wave are produced via the two-photon exchange process $e^+e^- \to \gamma\gamma \to K^0\bar{K}^0$, and the production of $K^0\bar{K}^0$ in the even partial wave with the emission of a soft photon which is undetected by the experimental apparatus, in other words, the allowed radiative decay of $\phi \to K^0\bar{K}^0\gamma$. We discuss first the intrinsic background due to the two-photon process.

The total rate for $e^+e^- \to \gamma\gamma \to K^0\bar{K}^0$ with the pair in the S state was estimated in Ref. 1 and was found to be extremely small,

$$r_S = \frac{e^+e^- \to \gamma\gamma \to \bar{K}K(S\text{ wave})}{\sigma(e^+e^- \to \gamma \to \phi \to \bar{K}K)} \simeq 10^{-10}. \qquad (1)$$

This result is not surprising because the S-wave cross section is suppressed by a factor m_e^2 due to the conservation of the helicity at high energy. The production of a pair of $K^0\bar{K}^0$ in the D wave is, however, allowed by helicity conservation resulting in an amplitude which is *not* proportional to m_e but is nevertheless suppressed because of the D-wave centrifugal barrier. It is therefore important to find out the relative importance of the S- and D-wave amplitudes due to the two-photon exchange.

The two-photon D-wave $K^0\bar{K}^0$ amplitude is estimated by two different methods: The first assumes $f^0, f^{0\prime}$ dominance in the intermediate state connecting the 2γ and $K\bar{K}$ state. The unitarity can be used to calculate the absorptive part of $e^+e^- \to 2\gamma \to K^0\bar{K}^0$ (D state) in terms of the experimental $f_0 \to 2\gamma$ and $f_0 \to K^0\bar{K}^0$ widths. Assuming the real part is of the same order as the imaginary part, we have

$$r_D = 10^{-10}. \qquad (2a)$$

As an alternative to this f_0-dominance calculation, following recent works[2] on the calculation of the 2γ-exchange amplitude in $K_L \to \pi^0 e^+e^-$ and an older work of Cheng[3] on the C-conserving $\eta \to \pi^0 e^+e^-$, we also calculate the absorptive part of the 2γ D-wave $K^0\bar{K}^0$ amplitude using the K^* vector-meson-dominance model. Using the experimental value $K^* \to K^0\gamma$ we again find

$$r_D = 2\times 10^{-10}. \qquad (2b)$$

Thus two different models yield 2γ D-wave $K\bar{K}$ cross sections which are consistent with each other and are similar to the S-wave background estimated by Ref. 1. Hence the intrinsic background is completely negligible for using the $K^0\bar{K}^0$ beam to test CP and CPT violation.

We now proceed to the main concern of the present work: the radiative background due to the decay mode $\phi \to K^0\bar{K}^0\gamma$ with $K^0\bar{K}^0$ in the S state. Because the photon here is soft, with a maximum momentum $q_{\max} < 20$ MeV, it may be difficult to distinguish such a decay from the genuine $\phi \to K^0\bar{K}^0$ events. Our calculation indicates a fairly large branching ratio

$$\rho = \Gamma(\phi \to K^0\bar{K}^0\gamma)/\Gamma(\phi \to K^0\bar{K}^0) \sim 10^{-5}\text{–}10^{-6}. \qquad (3)$$

Because of the small Q value of the $\phi \to K^0\bar{K}^0\gamma$ decay, it is reasonable to assume relative S-state angular momentum of the $K^0\bar{K}^0$ system. Since the scalar mesons $I=0$ $S^*(970)$ and the $I=1$ $\delta(980)$ are quite near to the $K^0\bar{K}^0$ threshold, it is reasonable to assume that they dominate the S-wave $K^0\bar{K}^0$. We are therefore led to the calculation of the $E1$ transition of $\phi \to S^*\gamma$ amplitudes. The relative importance of the $\phi \to K^0\bar{K}^0\gamma$ amplitude depends on the quark structure of these scalar mesons. Although a recent phenomenological analysis of the 2γ decay of these mesons indicates that they are likely to be a four-quark state,[4] we shall not restrict ourselves to this interpretation in estimating the $\Gamma(\phi \to S^*\gamma)$ width using the Thomas-Reich-Kuhn (TRK) sum rule.[5] To simplify our calculation further, we shall first neglect the contribution of the $\delta(980)$. The inclusion of this scalar meson will be discussed at the end of this Letter.

Saturating the TRK sum rule with the scalar meson $S^*(980)$, one has

$$\Gamma(\phi \to S^*\gamma) = \tfrac{2}{9}\,\alpha(e_i^2/m_i)(M-m)^2, \qquad (4)$$

where M and m are, respectively, ϕ and S^* masses and e_i and m_i are the charge and mass of the constituents.

(i) S^* is a two-quark $\bar{s}s$ state. While there is no doubt about interpreting ϕ as a $\bar{s}s$ bound state, S^*, which has a stronger coupling to $\bar{K}K$ than 2π, can be interpreted as dominantly $\bar{s}s$ or a four-quark state $\bar{s}s(\bar{u}u+\bar{d}d)$ (because the δ is almost degenerate in mass with the S^*, the interpretation of the four-quark state is more compelling).

If the S^* is a $\bar{s}s$ state which is the same as the ϕ vector meson, the $I=1$ δ scalar meson would not contribute to the TRK sum rule. Using $m_s \sim 400$ MeV, $e_i=\frac{1}{3}$, one has

$$\Gamma(\phi \to S^* \gamma) = 10^{-3}\ \mathrm{MeV}. \tag{5}$$

(ii) If the S^* is a four-quark $K\bar{K}$ state, which is likely to be the case, we must pretend that the ϕ meson is also a four-quark state in order to use the TRK sum rule. This assumption is likely not accurate. With this limitation in mind, using $m_i = m_K$ and $e_i=1$, one has

$$\Gamma(\phi \to S^* \gamma) = 3.3\times 10^{-3}\ \mathrm{MeV}, \tag{6}$$

which is a factor of 3.3 larger than the $\bar{s}s$ interpretation of S^*. Both approximations, Eqs. (5) and (6), may tend to overestimate the dipole transition between the only partially matched ϕ and S^*, assuming the S^* is a four-quark state.

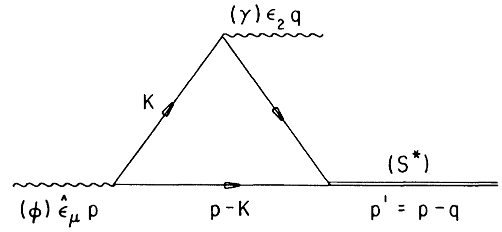

FIG. 1. Feynman diagram for $\phi \to S^* \sigma$ decay.

A possibly more quantitative approach for calculating the amplitude $M(\phi \to S^*\gamma)$ is to assume this decay proceeds through the charged K loop (Fig. 1). From general considerations, we can write

$$M(\phi \to S^*\gamma) = \hat{\varepsilon}_\mu(p)\varepsilon_\nu(q) M_{\mu\nu}(p^2,p'^2)$$

and

$$M_{\mu\nu}(p^2,p'^2) = [p_\nu q_\mu - (p\cdot q) g_{\mu\nu}] H(p^2,p'^2), \tag{7}$$

with p, p', and q the momenta of ϕ, S^*, and γ, and $\hat{\varepsilon}$ and ε the ϕ and γ polarization vectors. The Feynman diagram of Fig. 1 yields the following results:

$$M_{\mu\nu} = \frac{e g_\phi g}{(2\pi)^4} \int d^4K \frac{4K_\mu K_\nu}{(K^2-m^2)[(p-K)^2-m^2][(K-1)^2-m^2]}, \tag{8}$$

where g_ϕ is the ϕK^+K^- coupling with $g_\phi^2/4\pi = 1$. The $S^*K^+K^-$ coupling g is taken from a recent estimate $g^2/4\pi = 0.6$ GeV^2 which is quite reasonable.[4]

Using the usual Feynman parameters, we can split off from Eq. (8) a finite convergent integral for the $p_\nu q_\mu$ part of the amplitude to which the neglected graph with $\phi K\bar{K}\gamma$ "seagull" and $K\bar{K}$ bubble graph do not contribute;

$$H(M^2,M'^2) = \frac{e g_\phi g}{4\pi} \frac{1}{(M^2-M'^2)^{2*}} \int_0^4 \frac{dB}{\beta} \left[\beta(1-\beta)(M^2-M'^2) - [m^2-\beta(1-\beta)M^2] \ln \frac{m^2-\beta(1-\beta)M'^2}{m^2-\beta(1-\beta)M^2} \right],$$

where we put $p^2 = M^2$ and $p'^2 = M'^2$. The imaginary part of H can be readily extracted. For $M' \leq 2m$ which we assume here, this corresponds to the $K\bar{K}$ discontinuity in the M^2 channel;

$$\mathrm{Im}H(M^2,M'^2) = \frac{e g_\phi g}{12\pi} \left(\frac{M^2-4m^2}{M^2} \right)^{3/2} \frac{1}{(M^2-M'^2)^2} \left[\frac{1}{2(1-4m^2/M^2)^{1/2}} \ln \frac{1+(1-4m^2/M^2)^{1/2}}{1-(1-4m^2/M^2)^{1/2}} \right]. \tag{9}$$

The right-hand side of Eq. (9) has a numerical value of 0.15 GeV^{-1}. For the calculation of the real part, it is sufficiently accurate to approximate the parentheses on the right-hand side of Eq. (9) by 1 and use it in the "dispersion integral." A straightforward calculation shows the ReH is much smaller than ImH. We thus find

$$\Gamma(\phi \to S^*\gamma) = 6\times 10^{-5}\ \mathrm{MeV}, \tag{10}$$

an estimate smaller than the one based on the TRK sum rule Eqs. (5) and (6).

We can now calculate $\Gamma(\phi \to K^0\bar{K}^0\gamma)$ using the $S^*K^0\bar{K}^0$ coupling[4] in the tree diagram with an intermediate S^* exchange and integrate over the phase space to get

$$\rho = \frac{\rho(\phi \to K^0\bar{K}^0\gamma)}{\Gamma(\phi \to K^0\bar{K}^0)} \sim 3\times 10^{-6\pm 0.5} \tag{11}$$

with the uncertainties coming from $g_{S^*}K\bar{K}$ and Γ_{S^*}.[6]

Our estimate of ρ in Eq. (11) may limit the ability of the future ϕ meson factor as a facility to measure precisely the small (10^{-6}) CP-violation parameter (ε, $K_S \to 3\pi$, etc.) for the $K^0\bar{K}^0$ complex. Thus "genuine" CP-violating decays such as $e^+e^- \to \phi \to K_S^0 K_L^0$ ($K_S^0 \to 3\pi^0$, $K_L^0 \to 3\pi$) may be difficult to distinguish from the events coming from the CP-

conserving radiative background effects.

Another element of uncertainty which enters into our calculation is the contribution of the isovector scalar meson δ. Within the validity of the four-quark model, the contribution of δ and S^* interferes destructively in the $\phi\to K^0\bar{K}^0\gamma$ mode and constructively in the $\phi\to K^+K^0\gamma$ mode. Because of their somewhat different masses and their very different widths, we expect only partial cancellation in the $K^0\bar{K}^0\gamma$ mode. The decay $K^+K^-\gamma$, which is easier to measure, could play a useful role in checking future theoretical calculations.

More precise experimental information on $\phi\to\pi^+\pi^-\gamma$, with $\pi^+\pi^-$ coming from S^* decay, is needed to help further calculations on $\phi\to K^0\bar{K}^0\gamma$. This information may provide the best way to calculate this process. We would like to point out that the present experimental upper limit for $B(\phi\to\pi^+\pi^-\gamma)$ is only 7×10^{-3} and is about 2 orders of magnitude larger than our present estimate.

In conclusion, we suggest further theoretical calculations and more experimental work need to be done on the background problem.

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[a]Permanent address: Department of Physics, Tel Aviv University, Tel Aviv, Israel.

[b]Permanent address: Centre de Physique Théorique Ecole Polytechnique, 91128 Palaiseau, France.

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[6]We get similar results for $\phi\to K^0\bar{K}^0\gamma$ from Eqs. (5) and (6). The large value of ρ in Eq. (11) is due to the fact $(M^2-M'^2)^{-2}$ in Eq. (9).