Search for the scalar $a_0$ and $f_0$ mesons in the $\phi$ radiative decays.

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Abstract

The potentialities of the production of the $a_0$ and $f_0$ mesons in the $\phi$ radiative decays are considered based on a new two-channel analysis of the $\pi\pi$ scattering in an energy region near 1 GeV. We predict $BR(\phi \to \gamma f_0(980)) \sim 10^{-5} - 10^{-4}$ that is a great value for the decay forbidden by the Okubo-Zweig-Iizuka rule. We discuss the four-quark, $K\bar{K}$-molecule and two-quark scenarios for the $a_0$ and $f_0$ mesons. It is presented arguments that the $e^+e^-$-colliders and especially the $\phi$ factories give the possibility to choose a single one out of them.

The central problem of light hadron spectroscopy has been the problem of the scalar $f_0(980)$ and $a_0(980)$ mesons. It is well known that these states possess peculiar properties from the naive quark ($q\bar{q}$) model point of view, see, for example [1–3]. To clarify the nature of these mesons a number of models has been suggested. It was shown that all their challenging properties could be understood [1–3] in the framework of the four-quark ($q^2\bar{q}^2$) MIT-bag model with symbolic quark structure $f_0(980) = s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$ and $a_0(980) = s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$. Along with the $q^2\bar{q}^2$ nature of $a_0(980)$ and $f_0(980)$ mesons the possibility of their being the $K\bar{K}$ molecule is discussed. During the last few years it was established [4–6] that the radiative decays of the $\phi$ meson $\phi \to \gamma f_0 \to \gamma\pi\pi$ and $\phi \to \gamma a_0 \to \gamma\eta\pi$ could be a good guideline in distinguishing the $f_0$ and $a_0$ meson models. The branching ratios are...
considerably different in the cases of naive quark, four-quark or molecular models. As has been shown [4–6], in the four quark model the branching ratio is

$$BR(\phi \to \gamma f_0(q^2\bar{q}^2) \to \gamma\pi\pi) \approx BR(\phi \to \gamma a_0(q^2\bar{q}^2) \to \gamma\pi\eta) \sim 10^{-4},$$

and in the $K\bar{K}$ molecule model it is

$$BR(\phi \to \gamma f_0(K\bar{K}) \to \gamma\pi\pi) \approx BR(\phi \to \gamma a_0(K\bar{K}) \to \gamma\pi\eta) \sim 10^{-5}.$$

Currently also an interest in an old interpretation of the $f_0$ meson being an $s\bar{s}$ state is rekindled, despite the fact that the almost ideal mass degeneracy of the $f_0$ and $a_0$ mesons is difficult to understand in this case. In spite of this fact, the $s\bar{s}$ scenario is discussed in the current literature as one possible model of the $f_0$ meson structure. It is easy to note that in the case of an $s\bar{s}$ structure of the $f_0$ meson $BR(\phi \to \gamma f_0 \to \gamma\pi\pi)$ and $BR(\phi \to \gamma a_0 \to \gamma\pi\eta)$ are different by factor of ten, which should be visible experimentally.

In the case when $f_0 = s\bar{s}$ the suppression by the OZI rule is absent and the evaluation gives [4,6]

$$BR(\phi \to \gamma f_0(s\bar{s}) \to \gamma\pi\pi) \simeq 5 \cdot 10^{-5},$$

whereas for $a_0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ the decay $\phi \to \gamma a_0 \to \gamma\pi\eta$ is suppressed by the OZI rule and is dominated by the real $K^+K^-$ intermediate state breaking the OZI rule [4,6]

$$BR(\phi \to \gamma a_0(q\bar{q}) \to \gamma\pi\eta) \simeq (5 \div 8) \cdot 10^{-6}.$$

Let us note that in the case of the $\phi \to \gamma\eta'$ decay allowed by the OZI rule one expects $BR(\phi \to \gamma\eta') \simeq (0.5 \div 1) \cdot 10^{-4}$.

Imposing the appropriate photon energy cuts $\omega < 100$ MeV, one can show that the background reactions $e^+e^- \to \rho(\omega) \to \pi^0\omega(\rho) \to \gamma\pi^0\pi^0$, $e^+e^- \to \rho(\omega) \to \pi^0\omega(\rho) \to \gamma\pi^0\eta$ and $e^+e^- \to \phi \to \pi^0\rho \to \gamma\pi^0\pi^0(\eta)$ are negligible in comparison with the scalar meson contribution $e^+e^- \to \phi \to \gamma f_0(a_0) \to \gamma\pi^0\pi^0(\eta)$ for $BR(\phi \to \gamma f_0(a_0) \to \gamma\pi^0\pi^0(\eta))$ greater than $5 \cdot 10^{-6}(10^{-5})$. 

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Let us consider the reaction $e^+e^- \rightarrow \phi \rightarrow \gamma (f_0 + \sigma) \rightarrow \gamma \pi^0 \pi^0$ with regard to the mixing of the $f_0$ and $\sigma$ mesons. We consider the one loop mechanism of the $R$ meson production, where $R = f_0, \sigma$, through the charged kaon loop, $\phi \rightarrow K^+K^- \rightarrow \gamma R$, see [4–6]. The whole formalism in the frame of which we study this problem is discussed in [6]. The parameters of the $f_0$ and $\sigma$ mesons we obtain from fitting the $\pi\pi$ scattering data, see [6].

In the four-quark model we consider the following parameters to be free: the coupling constant of the $f_0$ meson to the $K\bar{K}$ channel $g_{f_0K^+K^-}$, the coupling constant of the $\sigma$ meson to the $\pi\pi$ channel $g_{\sigma\pi\pi}$, the constant of the $f_0 - \sigma$ transition $C_{f_0\sigma}$, the ratio $R = g^2_{f_0K^+K^-}/g^2_{f_0\pi^+\pi^-}$, the phase $\theta$ of the elastic background and the $\sigma$ meson mass. The mass of the $f_0$ meson is restricted to the region $0.97 < m_{f_0} < 0.99$ GeV. We treat the $\sigma$ meson as an ordinary two-quark state $g_{\sigma K^+K^-} = g_{\sigma\pi^+\pi^-}/2$. One gets $g_{\sigma K^+K^-} = \sqrt{\lambda} g_{\sigma\pi^+\pi^-}/2 \simeq 0.35 g_{\sigma\pi^+\pi^-}$. So the constant $g_{\sigma K^+K^-}$ (and $g_{\sigma\eta\eta}$) is not essential in our fit.

As for the reaction $e^+e^- \rightarrow \gamma \pi^0\eta$ the similar analysis of the $\pi\eta$ scattering cannot be performed directly. But, our analysis of the final state interaction for the $f_0$ meson production show that the situation does not changed radically, in any case in the region $\omega < 100$ MeV. Hence, one can hope that the final state interaction in the $e^+e^- \rightarrow \gamma a_0 \rightarrow \gamma \pi\eta$ reaction will not strongly affect the predictions in the region $\omega < 100$ MeV. Based on the analysis of $\pi\pi$ we predict the quantities of the $BR(\phi \rightarrow \gamma a_0 \rightarrow \gamma \pi\eta)$ in the $q\bar{q}^2$ model, $K\bar{K}$ model and the $q\bar{q}$ model where $f_0 = s\bar{s}$ and $a_0 = (u\bar{u} - d\bar{d})/\sqrt{2}$.

The fitting shows that in the four quark model ($g^2_{f_0K^+K^-}/4\pi > 1$ GeV$^2$) a number of parameters describe well enough the $\pi\pi$ scattering in the region $0.7 < m < 1.8$ GeV. We predict $BR(\phi \rightarrow \gamma (f_0 + \sigma) \rightarrow \gamma \pi\pi) \sim 10^{-4}$ and $BR(\phi \rightarrow \gamma a_0 \rightarrow \gamma \pi\eta) \sim 10^{-4}$ in the $q\bar{q}^2$ model.

In the model of the $K\bar{K}$ molecule we get $BR(\phi \rightarrow \gamma (f_0 + \sigma) \rightarrow \gamma \pi\pi) \sim 10^{-5}$ and $BR(\phi \rightarrow \gamma a_0 \rightarrow \gamma \pi\eta) \sim 10^{-5}$.

In the $q\bar{q}$ model the $f_0(a_0)$ meson is considered as a point-like object, i.e. in the $K\bar{K}$ loop, $\phi \rightarrow K^+K^- \rightarrow \gamma f_0(a_0)$ and in the transitions caused by the $f_0 - \sigma$ mixing we consider both the real and the virtual intermediate states. This model is different from $q\bar{q}$ model by
the coupling constant which is $g_{f_0K^+K^-}^2/4\pi < 0.5 \text{ GeV}^2$. In this model we obtain $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi) \simeq 5 \cdot 10^{-5}$ and taking into account the imaginary part of the decay amplitude only, as the main one, we get $BR(\phi \rightarrow \gamma a_0(q\bar{q}) \rightarrow \gamma\pi\eta) \simeq 8 \cdot 10^{-6}$.

Notice that we could not find the parameters at which the data on the $\pi\pi$ scattering are described well but the $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi)$ is less than $10^{-5}$. Or, more precisely, we could get $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi) \simeq 10^{-5}$, only if we dropped out the real part of the $K^+K^-$ loop in the $\phi \rightarrow K^+K^- \rightarrow \gamma(f_0 + \sigma)$ decay amplitude, otherwise we got $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi) > 4.5 \cdot 10^{-5}$. Forgetting the possible models, one can say that from the $\pi\pi$ scattering results $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi) > 10^{-5}$, that is enormous for the suppressed by the OZI rule decay.

The experimental data from SND detector, submitted to this conference, support the four quark nature of the $f_0$ and $a_0$ mesons, see [7,8].

The figures below show the results of fitting in the $q^2\bar{q}^2$ model for the parameters: $\theta = 60^\circ$, $R = 2.0$, $g_{f_0K^+K^-}^2/4\pi = 0.72 \text{ GeV}^2$, $g_{f_0\pi\pi}^2/4\pi = 1.76 \text{ GeV}^2$, $C_{f_0\sigma} = -0.17 \text{ GeV}^2$, $m_\sigma = 1.47 \text{ GeV}$, $m_{f_0} = 0.98 \text{ GeV}$. The effective width of the $f_0$ meson $\Gamma_{eff} \simeq 60 \text{ MeV}$. The $BR_{f_0+\sigma}(BR_{f_0}) = 3 \cdot BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi^0\pi^0)(3 \cdot BR(\phi \rightarrow \gamma f_0 \rightarrow \gamma\pi^0\pi^0)) = 1.18(1.43) \cdot 10^{-4} \text{ at } \omega < 250 \text{ MeV}$ and $BR_{f_0+\sigma}(BR_{f_0}) = 0.63(0.6) \cdot 10^{-4} \text{ at } \omega < 100 \text{ MeV}$. 
FIG. 1. (a) The inelasticity $\eta^{I=0}_{L=0}$. (b) The phase $\delta^{I=0}_{L=0}$.

FIG. 2. (c) The spectrum of the differential cross section $d\sigma(e^+e^- \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi^0\pi^0)/d\omega$ with mixing of the $f_0$ and $\sigma$ mesons). The dashed line is the spectrum of the $f_0$ meson without mixing with the $\sigma$ meson.
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