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ϕ Radiative Decays and Scalar Meson Structure

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Abstract

It is interesting to study radiative decays of mesons in the mass region of 1–2 GeV at RCNP for investigating the details of hadron structure. Among the decays, ϕ radiative decays into $f_0(975)$ and $a_0(980)$ mesons are not measured yet, and studies of these decays could provide important clues on their substructures. Furthermore, it is likely that the studies open up the field of exotic mesons.

1. Introduction

Quark models have been successful in explaining many properties of hadrons. Most mesons in the 1–2 GeV region are considered to be understood in nonrelativistic $q\bar{q}$ type models. However, there are predictions of exotic mesons which are not fitted into the $q\bar{q}$ category. For example, they are bound-$K\bar{K}$, $q^2\bar{q}^2$, glueball, and hybrid mesons. Especially, kaons are stable mesons so that it is no wonder that they form a bound state. Because the two-kaon mass is $2m_{K^\pm}$=987 MeV, the bound state should appear in the mass region 980 MeV if it exists. There are candidates of the kaon bound state: $f_0(975)$ and $a_0(980)$. The $q\bar{q}$ type models have difficulty in explaining narrow decay widths of these mesons. As discussed in section 2, calculated decay widths of f_0 in $q\bar{q}$ models are about twenty times larger than the experimental one. Because this difficulty is not enough to exclude the $q\bar{q}$ picture completely, it is important to test the substructure in other processes.

ϕ radiative decays into these mesons could be useful in discriminating among possible structure models. It is because the decays are electric dipole (E1) transitions. The E1 operator is sensitive to spatial distribution of electric charges. Sizes of a $q\bar{q}$ bound state and a $K\bar{K}$ bound state are expected to be much different. This is obvious because the $K\bar{K}$ molecule is supposed to be a loose bound state of K and $\bar{K}$ by noting that the scalar-meson masses are slightly below the $K\bar{K}$ threshold. The analogy of the $K\bar{K}$ molecule in nuclear physics is the deuteron, which exists just below the n-p threshold and it is the loose bound state of the proton and the neutron. From the above consideration, we expect that the ϕ-radiative-decay widths differ widely in various substructure models.

The best facility for measuring the ϕ radiative decays is a ϕ factory. There are ϕ factory proposals at Frascati, KEK, Novosibirsk, and UCLA [1]. The Frascati ϕ factory is already approved and it will be built in a few years. As it is shown in section 3, decay widths are very small so that it would not be easy to measure the decays at RCNP. However, it is still worth while measuring them in an independent way, e.g. p+d$\rightarrow^3$He+M ($\rightarrow$M$'\gamma$) [2].

The purpose of this talk is to point out why the ϕ radiative decays are important and what the decay widths are in various models [3]. However, our calculations are very naive estimates, so that much detailed theoretical analyses are needed in comparison with future experimental data.

We first discuss the issue of strong decay widths of the scalar mesons in section 2. Then, the radiative decay widths are estimated by assuming various structures for the scalar mesons.

2. Strong decay widths

There are "evidences" against the $q\bar{q}$ picture for the scalar mesons f_0 and a_0. First, these mesons exist just below the $K\bar{K}$ threshold, so that they could be $K\bar{K}$ bound states similar to the deuteron in nuclear physics. Second, experimental data indicate strong couplings of these mesons to the $K\bar{K}$ channel, which violates the OZI rule. Third, their $\gamma\gamma$ couplings calculated in $q\bar{q}$ models are much larger than experimental data. Forth, calculated strong-decay widths in $q\bar{q}$ models are much larger than data.

In this section, we discuss the last "evidence", the strong-decay-width problem. Decay widths of most mesons in the 1 GeV region are well described by $q\bar{q}$ models. However, it is almost impossible to explain the narrow decay widths of the scalar mesons. In the following, the strong decay of f_0 is discussed in the quark-model framework of Ref. [4].

It is not straightforward to describe strong-decay processes because they are non-perturbative and because relativity could be important in light-meson decays. Furthermore, final-state interactions would not be simple. In Ref. [4], we simply extended existing decay models. There are two major decay models: a $^3S_1$ model for the $q\bar{q}$ creation and a $^3P_0$ model. If the $q\bar{q}$ pair is created from a gluon splitting, a natural quantum state of the pair is the $^3S_1$ state, as it was proposed in the original Cornell paper for charmoniums. However, a phenomenological decay model $^3P_0$ has been widely used. As a physical interpretation, we may justify the $^3P_0$-$q\bar{q}$ model by considering color-flux fluctuations. Because of the existence of strong final-state interactions, it is rather difficult to discriminate between these models. In Ref. [4], strong decays of mesons into two pions were investigated in both models with consideration of the pion size and the final-state interactions.

Our typical results are shown in Fig.1, where our theoretical results for two-pion decays are compared with experimental data. A coupling constant for the $q\bar{q}$ creation is determined by the experimental $\rho \to \pi\pi$ decay width. As it was expected, the calculated decay widths are very sensitive to the pion size. If we take the 0.29 fm pion size, most decays are well explained. However, we still cannot explain the scalar meson decay $f_0 \to \pi\pi$ at all. Theoretical decay widths are in the range of 500–1000 MeV, which is badly in contradiction to the experimental one.

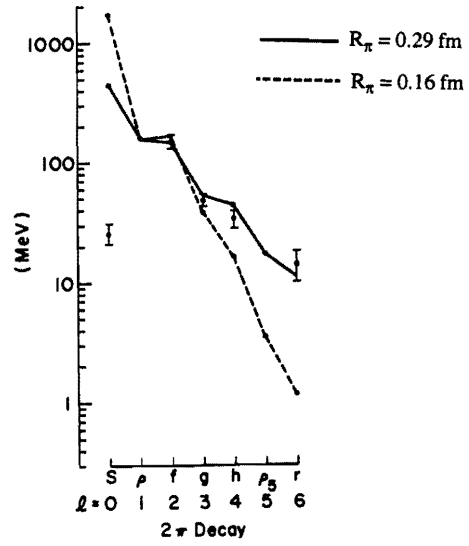

Fig. 1 Strong decay widths of $M \to \pi\pi$.

According to the version of the Review of Particle Properties in 1992 [5], the total decay width is 47 MeV and the branching ratio of $f_0 \to \pi\pi$ is 78.1%, so that the two pion decay width is supposed to be 37 MeV. As we mentioned, the decay models are not well established due to problems of final-state interactions, hadron wave functions, relativity, and decay models. However, it is peculiar that only f_0 (and a_0) cannot be described by the models even though almost all other mesons are explained. The difference of an order of magnitude between the theoretical result and the data is considered to be too large even if these problems are taken into account. Even if final state interactions are considered between final pions, it is impossible to explain the narrow width, unless there exists a strong repulsive interaction *only* in the S-wave $\pi\pi$ channel. Our calculation is not the only one which suggests the issue of the f_0 decay. More than several people have investigated the strong-decay problem, and they consistently obtained very large decay widths. In these calculations, they used different decay models and various wave functions; however, the results are always in the range of 500–1000 MeV.

The situation is similar in the case of a_0 meson. It decays into $\pi\eta$ dominantly and the total decay width is 57 MeV experimentally [5]. In the $q\bar{q}$ model, the decay width ratio $\Gamma(f_0 \to \pi\pi)/\Gamma(a_0 \to \pi\eta)$ is approximately 4, so that the theoretical width is larger than the data.

From the difficulty of strong decay widths together with other problems, it is natural to consider the f_0 and a_0 mesons as non-$q\bar{q}$ type mesons. For example, these narrow widths are understood in the $K\bar{K}$ picture as a natural consequence of weak binding.

3. ϕ radiative decays

There are evidences against the $q\bar{q}$ picture for the scalar mesons f_0 and a_0 as discussed in the previous section. However, these are not enough to exclude the $q\bar{q}$ picture completely. As an independent test, we may use ϕ radiative decays into the scalar mesons f_0 and a_0, which we denote S in this section. The radiative decays are, as we discussed in section 1, electric dipole transitions; hence, their decay widths are very sensitive to the internal structure.

Currently, the experimental upper bound of the branching ratio $BR(\phi \to f_0\gamma)$ is 2×10^{-3} and it is 5×10^{-3} for $BR(\phi \to a_0\gamma)$ [5]. If the ϕ factory is completed, these decays will be measured. However, it is also important to measure the decays in a completely different method, for example, by using future RCNP facility.

In the following, we discuss how the decay widths differ in various substructure models. This kind of research is still in the early stage, so the following calculations are merely rough estimates.

[**$q\bar{q}$ structure**] First, we assume that the f_0 meson is a $s\bar{s}$ bound state. Then, the OZI-allowed E1 decay width $\Gamma[\phi(s\bar{s}) \to f_0(s\bar{s})\gamma]$ is estimated from other E1 decay widths by taking into account the expression $\Gamma(E1) \sim e^2R^2E_\gamma^3$, where e is the charge factor, R is the hadron size, and E_γ is the photon energy. For example, we may use the observed charmonium decay width $\Gamma(\chi_{c0} \to J/\psi\gamma) = 0.092$ MeV. Taking into the quark charge, the hadron size, the photon energy, and a spin factor in the expression of the E1 width, we obtain $BR(\phi \to f_0\gamma) \approx 1 \times 10^{-5}$. We also used other E1 decays for the estimate, and obtained values are approximately equal to 10^{-5}.

If f_0 and a_0 are both ordinary mesons, namely $f_0 = (u\bar{u} + d\bar{d})/\sqrt{2}$ and $a_0 = (u\bar{u} - d\bar{d})/\sqrt{2}$, the both radiative decays are OZI-violating processes. Therefore, decay widths are supposed to be significantly smaller than the above OZI-allowed estimate 1×10^{-5}, and we expect the branching ratio $BR \lesssim 10^{-6}$.

[**$K\bar{K}$ structure**] Second, we discuss the case of $K\bar{K}$ molecules. In this picture, we consider the following process. ϕ decays into K^+ and K^-, either K^+ or K^- radiates a photon, then K^+ and K^- form a bound state S as shown in Fig. 2(b) or 2(c). Because the $\phi K\bar{K}$ coupling is given by $g_\phi\phi_\mu j^\mu$ with $j^\mu = iK^\dagger(\vec{\partial}^\mu - \overleftarrow{\partial}^\mu)K$, there is a process shown in Fig. 2(a) by the minimal substitution.

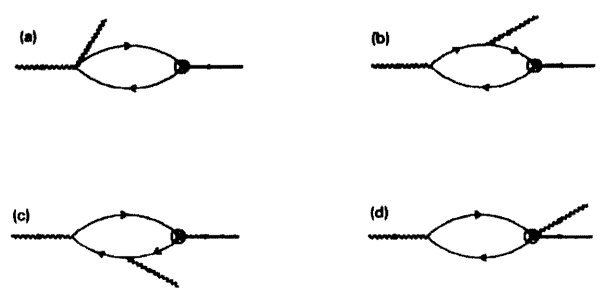

Fig. 2 Radiative decays $\phi \to K\bar{K}\gamma \to S\gamma$.

Physics meaning of Fig. 1(d) is not obvious at first hand. Because S is a loose bound state of K and $\bar{K}$, the kaon loop momenta cannot be infinite quantities. So we introduce

a momentum cutoff $\phi(|\vec{p}|)$ given by a $K\bar{K}$ wave function at the $SK\bar{K}$ vertex. This extra momentum dependence produces a current by the minimal substitution $\vec{p} \to \vec{p} - e\vec{A}$. This current is called "interaction current", which does not appear in point-like field theories. Because the momentum cutoff $\phi(|\vec{p}|)$ was introduced at the $SK\bar{K}$ vertex, K and $\bar{K}$ annihilate into S with a finite distance controlled by the cutoff. The interaction current is associated with the current flow over the finite distance at the vertex [6]. Fortunately, the photon energy in $\phi \to S\gamma$ is about 40 MeV, which is thought to be in the long wavelength region, so that the details of the interaction current are not important. We simply expand $\phi(|\vec{p} - e\vec{A}|)$ in the Taylor series of $e\vec{A}$, then take the first order term as the interaction current.

Employing the dipole cutoff, which is similar to the $K\bar{K}$ molecule wavefunction of a Toronto group, we obtain $BR(\phi \to f_0\gamma) \approx 4 \times 10^{-5}$. The branching ratio $BR(\phi \to a_0\gamma)$ is roughly equal to the above value. Momentum cutoff effects are significant, and the ratio becomes much smaller than the calculated one in a point-like theory. However, it is still much larger than the $q\bar{q}$ model predictions, so that we could at least discriminate between the $q\bar{q}$ model and the $K\bar{K}$ one.

[**$qq\bar{q}\bar{q}$ structure**] Even though quark contents of the $K\bar{K}$ molecule and $ns\bar{n}\bar{s}$ (where n denotes u or d quark) are the same, their dynamical structures are very different. If two color singlets are well separated and if they could be identified, the meson is a $K\bar{K}$ bound state rather than a four-quark bound state. If the color singlets are not identified, the meson should be considered as a four-quark state. It is unfortunate that strong decays of the four-quark bound state are little understood, so we cannot address ourselves to the radiative decay widths. However, we could study the relation between the decay-width ratio $\Gamma(\phi \to f_0\gamma)/\Gamma(\phi \to a_0\gamma)$ and the internal structure. The E1 operator is given by the constituent charge e_i and the vector distance $\vec{r}_i$ as $\vec{D} = \sum e_i \vec{r}_i$. Neglecting the spatial structure and simply counting constituent charges, we obtain rough estimates of the ratio.

If the scalar mesons are $K\bar{K}$-like "bags", they are expressed $f_0 = (u\bar{s})(\bar{u}s) + (d\bar{s})(\bar{d}s)$ and $a_0 = (u\bar{s})(\bar{u}s) - (d\bar{s})(\bar{d}s)$. Then, E1 matrix elements are given by $M(f_0) \sim (e_u + e_{\bar{s}}) + (e_d + e_{\bar{s}}) = 1$ and $M(a_0) \sim (e_u + e_{\bar{s}}) - (e_d + e_{\bar{s}}) = 1$. Therefore, the decay width ratio is $R(a_0/f_0) \approx 1$.

If the mesons are diquark-antidiquark-like "bags", they are expressed $f_0 = (us)(\bar{u}\bar{s}) + (ds)(\bar{d}\bar{s})$ and $a_0 = (us)(\bar{u}\bar{s}) - (ds)(\bar{d}\bar{s})$. Then, E1 matrix elements are given by $M(f_0) \sim (e_u + e_s) + (e_d + e_s) = -1/3$ and $M(a_0) \sim (e_u + e_s) - (e_d + e_s) = 1$. Therefore, the decay width ratio is $R(a_0/f_0) \approx 9$. This ratio is much different from the $K\bar{K}$-like-bag result, so that not only the absolute decay width but also the decay-width ratio provides important information on the internal structure.

If the scalar mesons are $\pi\eta$ or $\eta\eta$-like "bags", they are expressed $f_0 = (u\bar{u})(s\bar{s}) + (d\bar{d})(s\bar{s})$ and $a_0 = (u\bar{u})(s\bar{s}) - (d\bar{d})(s\bar{s})$. Then, E1 matrix elements are given by $M(f_0) \sim [(e_u + e_{\bar{u}}) - (e_s + e_{\bar{s}})] + [(e_d + e_{\bar{d}}) - (e_s + e_{\bar{s}})] = 0$ and $M(a_0) \sim [(e_u + e_{\bar{u}}) - (e_s + e_{\bar{s}})] -$

$[(e_d + e_{\bar{d}}) - (e_s + e_{\bar{s}})] = 0$. In this case, more sophisticated analysis are needed.

[glueball structure] If f_0 is a glueball, we estimate the quarkonium-glueball mixing by the observed $f_0 \to \pi\pi$ decay width and the calculated $^3P_0(q\bar{q}) \to \pi\pi$ width in section 2: the mixing $\lesssim \Gamma(f_0 \to \pi\pi)/\Gamma(^3P_0(q\bar{q}) \to \pi\pi) = 26/(500 - 1000) \lesssim 1/20$. Therefore, the decay width is $\Gamma(\phi \to f_0(glueball)\gamma) \lesssim \Gamma(\phi \to f_0(q\bar{q})\gamma)/20$. Using the results for $\Gamma(\phi \to f_0(q\bar{q})\gamma)$, we obtain $B.R.(\phi \to f_0\gamma) \lesssim 10^{-6}$.

Our estimates are summarized in the following table.

Constitution		Ratio $\Gamma(\phi \to \gamma a_0)/\Gamma(\phi \to \gamma f_0)$	Absolute B.R.
$K\bar{K}$	molecule="diffuse $K\bar{K}$"	1	$a_0 \simeq f_0 \simeq 4 \times 10^{-5}$
$q^2\bar{q}^2$	$K\bar{K}$-like "bag"$= (n\bar{s})(\bar{n}s)$	1	$a_0, f_0 \lesssim 10^{-6}$?
	DD-like "bag"$= (ns)(\bar{n}\bar{s})$	9	see Ref. 3
	$\pi\pi, \pi\eta$-like "bag"$= (n\bar{n})(s\bar{s})$	–	
$^3P_0(q\bar{q})$	$f_0(n\bar{n})$, $a_0(n\bar{n})$	–	$a_0, f_0 \lesssim 10^{-6}$
	$f_0(s\bar{s})$, $a_0(n\bar{n})$	≈ 0	$f_0 \simeq 1 \times 10^{-5}$
glueball	f_0	–	$f_0 \lesssim 10^{-6}$

Table 1. Estimated decay widths in various models.

4. Conclusions

Internal structures of the scalar mesons f_0 and a_0 have been controversial. Strong decay widths are too large to explain experimental ones in $q\bar{q}$ type quark models. ϕ radiative decays could be used for discriminating among various models because the decay widths differ widely: B.R.$=10^{-4} - 10^{-6}$ depending on the structure. It is useful to study the radiative decays at the future RCNP facility.

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