CAN THE SCALAR MESONS $a_0/f_0(980)$ BE DESCRIBED BY $K+\overline{K}$?

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The scalar mesons $f_0(980)$ and $a_0(985)$ are two of the best-verified states in the excited meson spectrum. They appear as narrow resonances in the 2π and $\eta\pi$ mass spectra, respectively, observed in hadroproduction reactions and in the decays of heavier particles such as the J/Ψ and the Z^0. Their relatively low mass and narrow width do not match well with quark-model expectations for the lightest scalar multiplet, fueling speculation that these states might be different in nature from conventional $q\overline{q}$ mesons. A variety of theoretical models have been put forward to explain these states, most notably the so-called "2-kaon molecule" model in which they appear as kaon-antikaon bound states. Within this picture, the radiative decays of the $\phi(1020)$ meson two two-pseudoscalar final states are expected to be dominated by f_0 and a_0 intermediate states, in spite of their appearance very near the edge of the available phase space. Recent experimental results from e^+e^- colliders have recently provided striking verification of this effect. Meanwhile, new work within a more general theoretical approach to the two-meson scattering problem has shown that the appearance of narrow scalar resonances near the two-kaon threshold is not a unique prediction of the molecule model, but are a consequence of the general principles of unitarity and chiral symmetry. The relative merits of these different viewpoints are examined in light of the ϕ decay data.

1 Introduction

Within the context of the quark model, the lightest L=1 mesons belong to the fundamental scalar nonet. The scalars appear as the first rung of a ladder of three nonets closely spaced in mass, with J^{PC} assignments 0^{++}, 1^{++} and 2^{++}. A tidy correspondence between the quark model and the observed spectrum of mesons has been achieved for the axial and tensor nonets, with central masses around 1.3 GeV/c^2. The widths of these states are governed by decay selection rules which determine the minimum number and angular momentum of light mesons in the final state, with the broadest states having allowed s-wave decays into 2 L=0 mesons. For example, the a1(1260) decays predominantly into $\rho\pi$ s-wave, with a partial width of several hundred MeV. Based upon this pattern, one should expect to find the fundamental scalar nonet with non-strange members in the mass range 1.2 - 1.3 GeV/c^2 and with 2-pseudoscalar decay widths of several hundred MeV. When one looks at the resonance structure in $\pi\pi$ scattering, however, what one sees instead is a scalar state just below 1.0 GeV/c^2 that is less than 100 MeV/c^2 in width observed through its interference with a broad non-resonant s-wave. This state has isoscalar quantum numbers and is called the $f_0(980)$. A similar narrow scalar state around 1.0 GeV/c^2 is seen in $\pi\eta$ scattering, called the $a_0(980)$.

Several reasons have been suggested for this apparent failure of the quark model in the scalar sector. One idea arises within the context of a coupled-channel analysis of 2-pseudoscalar s-wave scattering [1]. In this analysis, the $q\overline{q}$ scalars are put in with their conventional quark-model masses and couplings. It is shown that, as the couplings are increased from zero, the renormalized scalar propagator starts off looking like an ordinary Breit-Wigner peak centered at the quark-model mass with a width increasing with the coupling. For larger couplings, however, the shape deviates from a Breit-Wigner and large distortions appear in the tails at the locations of thresholds in coupled channels. These distortions are understood as rescattering effects in the final state, but they act very much like physical particles because they are associated with poles in the scattering amplitude that happen to lie near the real axis. Naively interpreting the observed masses and widths of such dynamical poles as the parameters of quark-model states, it is argued, has given rise to the problem of the scalars.

Another common explanation for the problem of the scalars is the glaring absence in the quark model of any account being taken of the $q\overline{q}$ condensate in the QCD vacuum. The condensate arises within an analysis of low-energy QCD that is built upon the light quarks of the QCD Lagrangian as the basic degrees of freedom instead of the constituent quarks of the quark model. One consequence of making the quarks very light is that the spectrum of physical states should exhibit chiral symmetry, where every positive parity mode has a degenerate partner with negative parity and vice versa. The fact that the pion has no scalar partner nearby in mass is explained within the context of sigma models by the mechanism of spontaneous symmetry breaking, whereby the pion emerges as a massless Goldstone boson and the lightest scalar (sigma meson) is pushed up in mass through its interaction with the $q\overline{q}$ background. This picture of a fundamental pion and sigma can be augmented by the explicit inclusion of light quarks upon which the vectors and the rest of the meson spectrum is built. The fundamental role played by the scalars and pseudoscalars with respect to the QCD vacuum sets them apart from the rest of the mesons in this picture, suggesting that the masses and structure of the scalars and pseudoscalars cannot be understood within the same framework that accounts for the rest of the $q\overline{q}$ meson spectrum, as the quark model attempts to do.

As a description of the dynamics of low-energy QCD, the sigma model is no doubt correct. But a clear statement of what this has to do with the failure of the quark model for the light scalars cannot be made until it is understood how the constituent quark is related to the fundamental fermion. The contrast between these two approaches can be stated as follows. The quark model has a clear relation to the meson spectrum, but inasmuch as it invokes the ill-defined constituent quark, its relation to QCD is an open question. The sigma model has a clear relation to QCD, but its relation to the meson spectrum is an open question (apart from its prediction of a light pion). This latter point is illustrated by the fact that no obvious candidate stands out in the meson spectrum to fit the role of the sigma meson.

The $a_0(980)$ and $f_0(980)$ mesons present a challenge to both models. Within the quark model, the naive assignment of these states to the fundamental scalar nonet is problematic. The explanation that these states are dynamical resonances arising from rescattering between coupled channels appears sound, but needs to be tested by experiment. Within the sigma model, the naive identification of the f_0 as the sigma begs the question of the identity of its twin, the a_0. An alternative explanation for these states within the context of the sigma model has recently been proposed [2]. Again the context of the calculation is a coupled-channel analysis of 2-pseudoscalar scattering, but instead of beginning with the quark model one starts with the Lagrangian of Chiral Perturbation Theory. Including only the leading-order interactions in the Lagrangian, but taking into account unitarity by summing over diagrams with any number of rescattering loops, the isoscalar and isovector scattering amplitudes exhibit narrow resonance structures just below 1 GeV. Their appearance there is not accidental, but coincides with the opening of the kaon-antikaon threshold.

Thus an unexpected convergence has appeared between two very different ways of looking at low-energy QCD regarding the nature of the f_0 and a_0, with the hypothesis that they are dynamical resonance phenomena associated with the opening of the $K\overline{K}$ threshold. They are dynamical in the sense that they are not present in the calculation at leading order, but appear when the infinite chain of rescattering loops is summed, as required by unitarity.

2 Structure

Besides the fact that the light a_0 and the f_0 lie very close to the $K\overline{K}$ threshold, they have another feature that supports their interpretation as dynamical resonances. Both states have quite large couplings to $K\overline{K}$ decay modes. For the f_0 the ratio $g_{2K}^2/g_{2\pi}^2$ is about 4 and for the a_0 the analogous ratio is about 1. For quark model states, by contrast (eg. the vectors), the lightest isoscalar and isovector states are expected to have suppressed couplings to strange decay modes. However in a rescattering picture, these states are not $q\overline{q}$ mesons but enhancements in the $\pi\pi$ and $\eta\pi$ scattering amplitude near the $K\overline{K}$ threshold that come about through intermediate kaon-antikaon loops. Thus any process that has kaons in the final state will be at least as strong or stronger than the corresponding non-strange process.

In this way it is seen that the somewhat obscure mathematical notion that these states arise from the unitarization of a one-loop scattering calculation actually has distinct consequences for their structure: they should behave like a low-energy kaon-antikaon pair. This is reminiscent of an old idea suggested by Weinstein and Isgur [3] that the $a_0(980)$ and $f_0(980)$ are weakly-bound kaon-antikaon states. Within the context of their potential model they found that the short-range interaction between the kaon and antikaon was sufficient to give a bound state with a binding energy of several MeV. Such a state has been called a $K\overline{K}$ *molecule*.

While there are structural similarities between the molecule and dynamical resonance models, it is obvious from the complexity of a coupled-channel analysis that the latter cannot be reduced to the former. This is why the two notions are not identified in this work. Nevertheless the molecule hypothesis is not in opposition to dynamic resonance pictures. Regardless of what mechanism gives rise to the binding, it is an intriguing question whether the *essential physics* involving the a_0/f_0 resonances can be subsumed into the properties of a single hypothetical bound $K\overline{K}$ state. In the limit where the contribution of infrared kaon loops dominates all other phenomena in the region around the $2K$ threshold one expects that the two viewpoints should be complementary. If however the interference with other 2-meson loops is important then nothing short of a full coupled-channels analysis will be adequate.

Other hypotheses for the structure of the light scalars are also found in the literature. The most noteworthy among these are the conventional $q\overline{q}$ hypothesis and the 4-quark exotic state. The $q\overline{q}$ hypothesis asserts that the structure of the light scalars is that of an L=1 meson with an unusual flavor signature, masses and widths. The 4-quark exotic state is distinguished from the molecule in that the former is confined within a typical bag radius of 1fm whereas the latter is not.

3 Phi radiative decays

It has long been known that the decays of the $\phi(1020)$ meson to γa_0 and γf_0 afford a unique opportunity to test models of the light scalars. In a landmark paper [4], Close, Isgur and Kumano calculated the partial width for this decay within the framework of a $K\overline{K}$ molecule. In particular they found

Table 1. Predictions for the ratio R of branching ratios for the reactions $(\phi \rightarrow \gamma a_0) : (\phi \rightarrow \gamma f_0)$

$q\overline{q}$ state	0:1
$K\overline{K}$ molecule	1:1
$qq\overline{qq}$ state	9:1

that the ratio R of branching ratios to the two scalar states was sensitive to the hypothesized structure. Their results are summarized in Table 1. The reason for the suppression of the a_0 relative to the f_0 in the $q\overline{q}$ model is the OZI rule: the f_0 has a large $s\overline{s}$ admixture as required by its strong $K\overline{K}$ coupling, whereas the I=1 a_0 has none. In the case of the molecule, the reason for the equality of the a_0 and f_0 branching ratios is the fact that the photon only couples to the K^+K^- piece of the $K\overline{K}$ wave function, which piece has equal projections onto the I=0 and I=1 partial waves. The assumption in that prediction is that the f_0 is pure isoscalar and the a_0 isovector, but it can be generalized to allow for isospin mixing. In the case of the 4-quark state, almost any value for R can be obtained by a suitable choice of flavor couplings. The value of 9 in the table emerges for one possible choice which illustrates that the 4-quark exotic offers a unique explanation for the case where the f_0 branch is strongly suppressed relative to the a_0. More generally, the couplings of the exotic a_0 and f_0 can be adjusted to give any value for R.

The predictions for the dynamic resonance models are difficult to interpret in terms of R because in such models the part of the amplitude coming from the kaon loops associated with the a_0 and f_0 peak is part of a 2K continuum and produces a non-Breit Wigner tail in the $\pi\eta$ and $\pi\pi$ invariant mass spectra, respectively, whose integral depends on how the a_0 and f_0 regions are defined (see Fig. 1). Nevertheless one would expect in the absence of strong interference with non-resonant background that the I=0 and I=1 yields should be comparable.

Experimental results for these decays have recently been published by SND [5] and KLOE [6]. A third experiment to measure these decays called RADPHI is underway at Jefferson Lab [7], with no published result at present. The SND results are shown in Fig. 1. Corresponding results from KLOE are shown in Fig. 2. The branching ratios to the respective final states are obtained by integrating over the peak and correcting for unseen decay modes of the a_0 and f_0. These are given in Table 2. The agreement between the two measurements is better than appears from the table because the SND result for the f_0 channel includes the entire $\pi^0\pi^0$ phase space, whereas KLOE

Table 2. Experimental results for the branching ratios of phi radiative decays in I=0 and I=1 partial waves. The statistical error is given first, followed by the systematic error.

channel	SND	KLOE
$\phi \to \gamma a_0$	$(0.88 \pm 0.14 \pm 0.09) \times 10^{-4}$	$(0.58 \pm 0.05 \pm 0.04) \times 10^{-4}$
$\phi \to \gamma f_0$	$(3.5 \pm 0.3 \pm 0.9) \times 10^{-4}$	$(2.4 \pm 0.6 \pm 0.2) \times 10^{-4}$
R	0.25 ± 0.04	0.24 ± 0.03

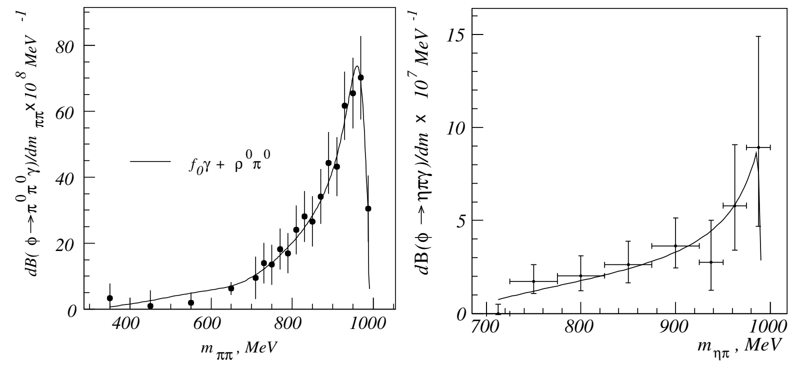

Figure 1. Results from VEPP-2M experiment SND for the decay $\phi \to \gamma\pi^0\pi^0$ (left) and $\phi \to \gamma\eta\pi^0$ (right). The prominent peak at high mass in the figures is attributed to the scalar resonances. The $\pi^0\pi^0$ spectrum also contains a small contribution from the decay $\phi \to \rho^0\pi^0$ where the ρ^0 is seen via its small decay branch to $\gamma\pi^0$.

reports only the integrated yield above 700 MeV/c^2 in $\pi\pi$ invariant mass. To a large extent this difference drops out in the ratio R.

4 Interpretation

These new data exhibit two surprising features: a large departure of the ratio R from the expected value of unity and a larger magnitude for the individual branching ratios than was anticipated.

The prediction that $R = 1$ is a general result that applies to any model in which the ϕ couples to the photon through intermediate $kaon - antikaon$ loops. This picture applies both to the coupled-channel analyses where the a_0 and f_0 are dynamical rescattering effects and the molecule model where they are $K\overline{K}$ bound states. Since the photon does not couple to the neutral kaon, only the K^+K^- loop contributes, whose projection onto final states of good

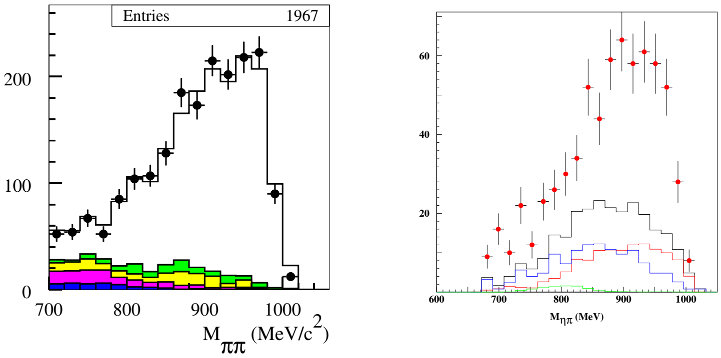

Figure 2. Results from DAΦNE experiment KLOE for the decay $\phi \to \gamma\pi^0\pi^0$ (left) and $\phi \to \gamma\eta\pi^0$ (right). The prominent peak at high mass in the figures is attributed to the scalar resonances. The histograms under the data in the plots indicate the expected contribution from backgrounds that are present in the final sample.

isospin yields a 1:1 ratio of I=0 to I=1.

In the molecule model in particular it is difficult to explain the observed ratio of 1:4. A very large isospin violation in the interactions is required, beyond what can be accounted for by the neutral-charged kaon mass difference. Within this model the fact that the kaon mass difference is comparable to the binding energy leads naturally to strong mixing between I=0 and I=1 in the mass eigenstates a_0 and f_0. But as long as these eigenstates remain more or less degenerate, that mixing is unable to explain a significant deviation of R from 1. The reasoning that leads to this conclusion is as follows.

We assume that the interaction vertices themselves respect isospin, and that ϕ radiative decays proceed through an intermediate charged-kaon loop. The scalar state formed when the two charged kaons annihilate in the s-wave is the superposition $\sin(\theta+\pi/4)a_0+\cos(\theta+\pi/4)f_0$ where θ is the scalar mixing angle. For example, if the a_0 were pure I=1 and the f_0 pure I=0 then $\theta = 0$ and the 1:1 ratio for the isospin-symmetric limit is obtained. However no matter what the value of the mixing angle, the intermediate scalar superposition state can always be written $\sin(\pi/4)|I = I > +\cos(\pi/4)|I = 0 >$ which is just a statement of isospin conservation at the scalar production vertex. In the case that the physical a_0 and f_0 are degenerate in mass, this isospin superposition propagates unchanged to the decay vertex, where the it couples to final states of good isospin $\pi\eta$ and $\pi\pi$ with relative amplitudes $\sin(\pi/4)$ and $\cos(\pi/4)$, respectively. A key to this argument is the observation that the physical

a_0 and f_0 states are degenerate in mass, or at least their splitting is small compared to their widths, so that significant oscillations between I=0 and I=1 does not take place during their lifetimes.

Close and Kirk have recently argued [8] based upon data taken in central pp collisions that there is a large mixing angle between the I=0 and I=1 components in the a_0/f_0 system. General arguments indicate that the source of particles formed at mid-rapidity in such high-energy collisions is isoscalar in character, which would lead to a ratio of 0 for centrally produced a_0/f_0 in the absence of mixing. From the experimental value of this ratio they deduce a mixing angle of $\tan^2(\theta) = 0.30 \pm 0.05$. The authors point out the remarkable similarity of their value of $\tan^2(\theta)$ to the measured value of 0.25 ± 0.05 for R in radiative ϕ decays. One issue not addressed by the authors is how they can identify the physical a_0 with the $\pi\eta$ channel and the physical f_0 with $\pi\pi$ even though the physical states contain strong admixtures of both I=0 and I=1 components. In addition to mixing, it would appear that a large isospin violation in the decay couplings are required.

The same argument described above for ϕ radiative decays would also prevent the large isospin-violating effect in these data from being arising simply from a_0/f_0 mixing. Repeating the argument in another way, if the a_0 and f_0 were really identical apart from isospin then the mixing angle would simply be a matter of definition and could have no observable consequences. Allowing for a small mass splitting does introduce mixing effects, but inasmuch as the physical a_0-f_0 mass difference is small compared to the widths, the interference between the two scalars cannot give rise to large isospin-violating amplitudes. This argument applies equally to the case of central production and to radiative ϕ decays.

The way that this problem can be resolved is to take into account interference between the resonant amplitude coming from the scalar intermediate states and the nonresonant background. It is well known that there is a strong nonresonant background in the I=0 channel that must be taken into account to understand the structure of the $\pi\pi$ s-wave below 1.2 GeV. Trying to understand this interference involves a comprehensive analysis of data from several 2-pseudoscalar channels and leads inevitably to the kinds of coupled-channel analyses presented in Refs. [1],[2]. In such a picture, the value of R is ill-defined because the resonance-background interference makes the extraction of a branching ratio for the resonant part model dependent. Instead it is simpler to directly compare the fit with the measured spectral decay rate, as shown in Fig. 3 for the analysis of Ref. [2]. Apart from sign ambiguities, the prediction has zero parameters. From this figures it appears that these data may be described quite well within such an approach.

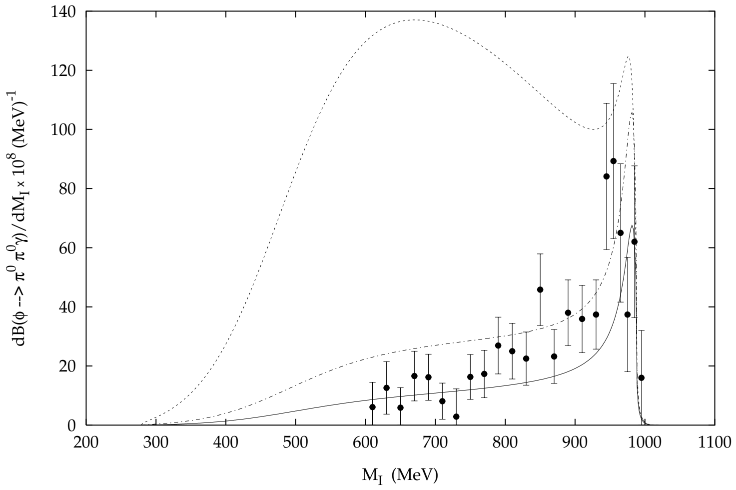

Figure 3. Comparison between coupled-channel calculation of Oset *et.al.* and early data from SND and CMD-2 for the reaction $\phi \to \gamma\pi^0\pi^0$. The different curves represent different signs for terms in the analysis that are not constrained by fits to other $\pi\pi$ scattering data.

Referring to Table 1 it may be asked why a small value for R may not b e taken as evidence for a conventional $q\overline{q}$ for the scalars. However this is effectively ruled out by the sheer magnitude of the individual $\phi \to f_0\gamma$ and $\phi \to a_0\gamma$ decay rates. For a conventional $q\overline{q}$ state the individual branching ratios are expected on the order of 10^{-5} [4] whereas the measured values in Table 2 are of order 10^{-4} or larger.

The SND collaboration interprets their results in the light of a $qq\overline{qq}$ model [5]. The curves in Fig. 1 show excellent agreement with the data, although this is not surprising in view of the fact that such a model is essentially unconstrained in its choice of couplings. The mainstay of the argument put forward for the $qq\overline{qq}$ interpretation is that the magnitude of the decays is too large to be explained in any other way. This conclusion would appear to be supported by Ref. [4] which predicts branching ratios on the order of 5×10^{-5}. However they arrive at that prediction based on an estimate for the effective range of the $K\overline{K}$ potential which is an unknown parameter in the molecule model. The effective range can be decreased without changing the scattering length, and doing so increases their prediction up to a limiting value of about 3×10^{-4}. The measured value falls just at the edge of the range allowed for the molecule, and so the $K\overline{K}$ bound-state model should not be excluded on this basis.

5 Conclusions

The $K\overline{K}$ bound-state model of the $a_0(980)$ and $f_0(980)$ is appealing because of how it explains a number of unusual properties of these states under a conceptually and calculationally simple hypothesis. This simplicity has enabled a straightforward prediction for the ratio R in radiative ϕ decays that is relatively robust within the model. Two independent experiments have now published results indicating that $R = 0.25 \pm 0.05$ rather than the expected $R = 1$, which can only be explained within the molecule model by anomalously large isospin-breaking effects in the scalar-pseudoscalar couplings.

Data taken in central production have been used to estimate the isospin mixing angle between the scalars, with the result $\tan^2(\theta) = 0.30 \pm 0.05$. It has been suggested that such mixing might also be responsible for the value of R in ϕ decays. The similarity of the values for θ obtained from these two very different experiments is interesting, but in order to understand the *phi* decay result in this way a large isospin violation is needed at an interaction vertex; mere mixing of the nearly-degenerate a_0/f_0 states is not sufficient.

Acknowledgments

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