Scalar meson properties from $D$-meson decays

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Decay amplitudes of $D(D_s) \to f_0(980)X$, $X = \pi, K$, are compared to experimental branching ratios with the aim of singling out the poorly known $D \to f_0(980)$ transition form factor in these amplitudes. Since the other elements of the amplitudes are either calculable in an effective QCD theory using operator product expansion or are known from experiment (e.g. the pion and kaon decay constants), we can take advantage of these reactions to constrain the transition form factors obtained in relativistic quark models [1]. In these models, the $f_0(980)$ wavefunction requires an unknown size parameter for both its non-strange $\bar{u}u(\bar{d}d)$ and strange $\bar{s}s$ components, which we fit to the $D(D_s)$ decay data.

1. MOTIVATION

Scalar mesons have been a recurrent topic over the past 30–40 years and while the $\sigma$ has been a longstanding open question since the 1960s, the $f_0(980)$ and $a_0(980)$ were firmly established in $\pi\pi$ scattering experiments in the 1970s [2]. The constituent structure of the scalar mesons, nevertheless, has been and still is a controversial issue. For a general overview we refer, for instance, to the Particle Data Group review [3] and references therein. The known $0^{++}$ mesons fall into two classes: near and about 1 GeV and in the region $1.3 \sim 1.5$ GeV. The scalar objects below 1 GeV form an $SU(3)$ flavor nonet. This nonet contains two isosinglets, an isotriplet and two strange isodoublets. Among these lighter scalars, the isosinglet $f_0(980)$ and the isotriplet $a(980)$ are fairly narrow: $\Gamma = 40 \sim 100$ MeV. Both couple strongly to the $KK$ channel and lie close to the $KK$ threshold at 987 MeV. This closeness to threshold distorts the shape of their resonant structure and the description of the $f_0$ and $a_0$ requires a coupled-channel scattering analysis.

The simple quark model views these scalar mesons as orbitally ($L = 1$) excited $\bar{q}q$ states and has been advocated by Törnqvist and Roos [4]. However, some studies [5] tend to favor four-quark configurations of the scalar mesons and so do coupled-channel analyses [6] or potential models of molecular states strongly coupled to $\pi\pi$ and $KK$ thresholds [7].

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In any case, the precise four-quark picture is still open to debate since a coupled-channel model implies two $\bar{q}q$ pairs while the configuration $\bar{q}^2q^2$ requires two di-quarks.

In the past few years, scalar mesons have emerged in three-body decays of heavy mesons such as $D \to \pi\pi\pi, \pi\pi\bar{K}, \bar{K}KK$ measured at CESR, DESY and Fermilab [8–16] and $B \to \pi\piK, \bar{K}KK$ decays observed at the dedicated $B$-meson facilities BaBar and Belle [17]. In particular, in Ref. [15], an experimental evidence for a light and broad scalar resonance in the $m_{\pi\pi}$ spectrum of the $D \to \pi\pi\pi$ decay was found, to be identified with the $f_0(600)$, and also a less pronounced $f_0(980)$ peak. Both the BaBar and Belle collaborations [17] report a distinctive peak around 1 GeV in the $m_{\pi\pi}$ spectrum of three-body $B$-decays.

Our interest in $D$-decays with an $f_0(980)$ in the final state is motivated by two relativistic quark model calculations of $B \to f_0(980)$ and $D \to f_0(980)$ transition form factors we have performed recently, one of which makes use of the dispersion relation approach, the other is being done within Covariant Light-Front Dynamics (CLFD) [1]. Both methods are explicitly covariant and require two size parameters that specify the unknown $f_0(980)$ wave function. In order to deduce these parameters from experiment, we fit $D(D_s) \to f_0(980)X$ branching fractions, where $X$ can be a pion or a kaon. The decay amplitudes are built within the naive QCD factorization approach which neglects hard-scattering effects between the spectator and any of the other final quarks. Annihilation topologies are not considered here. Since $m_c$ is less than half the value of $m_b$, non-perturbative contributions of order $\Lambda_{QCD}/m_c$ may be more important than in $B$-decay amplitudes and the factorization approach thus less reliable. Nonetheless, already at tree level, non-leptonic two-body decay channels of $D$-mesons can be reasonably reproduced within this simple factorization hypothesis. This is not the case for two-body $B$-decays, where penguin contributions are more important. Hence, the decay amplitudes are products of a short-distance part, calculated in perturbation theory, and hadronic matrix elements describing the long distance physics such as the pion or kaon decay constant and the $D \to f_0(980)$ form factors we are interested in.

### 2. DECAY AMPLITUDES IN THE FACTORIZATION APPROACH

At tree-level order the generic decay amplitudes for a $D$-meson decaying into a scalar $f_0(980)$ and a pseudoscalar meson $P$ are given by

$$A(D \to f_0P) = \frac{G_F}{\sqrt{2}} a_i f_P(m_D^2 - m_{f_0}^2) F^{D \to f_0}_{0} (m_P^2) V_{cq} V_{uq}^* \ .$$

(1)

Here, $G_F$ is the Fermi coupling constant, $f_P$ is the pseudoscalar decay constant, $V_{cq}$ and $V_{uq}$ are the CKM matrix elements with $q = d, s$ and $m_D$ and $m_{f_0}$ are the $D$- and $f_0(980)$-meson masses, respectively. Our main interest here is the $D \to f_0(980)$ transition form factor $F^{D \to f_0}_{0} (m_P^2)$. The short distance physics, beyond the scale $\mu = m_c$, is described by the effective coefficients $a_1 = C_1 + C_2/N_c$ and $a_2 = C_2 + C_1/N_c$ where $C_1(\mu)$ and $C_2(\mu)$ are the tree-operator Wilson coefficients taken at $\mu = m_c$ [18] and $N_c = 3$ is the number of colors. The amplitudes for penguin diagrams have the same structure, yet their contribution in $D$-decays is considerably smaller and usually neglected.

Using the above factorized amplitudes, the decay rates can be computed as

$$\Gamma(D \to f_0P) = \frac{1}{8\pi} \frac{|p|}{m_D^2} \frac{1}{\Gamma_D} |A(D \to f_0P)|^2 \ ,$$

(2)
Table 1

Experimental branching fractions for \( D \to f_0(980)X \) and \( D_s \to f_0(980)X \) (\( X = \pi, K \)) deduced from the corresponding three-body decays [8–16] with \( \mathcal{B}(f_0 \to \pi^+\pi^-) = 0.80 \pm 0.14 \) and \( \mathcal{B}(f_0 \to K^+K^-) = 0.11 \pm 0.02 \). \( \mathcal{F}(D^0 \to f_0\pi^0) \) is the fit fraction of the \( D^0 \to f_0\pi^0 \) decay.

| Experiment | \( \mathcal{B}(D^+ \to f_0\pi^+) \times \mathcal{B}(f_0 \to \pi^+\pi^-) \) | \( \mathcal{B}(D^+ \to f_0K^+) \times \mathcal{B}(f_0 \to K^+K^-) \) |
|-----------|-------------------------------------------------|-------------------------------------------------|
| E791      | \( (1.9 \pm 0.5) \times 10^{-4} \)               | \( (3.84 \pm 0.92) \times 10^{-5} \)               |
| FOCUS     | \( (3.2 \pm 0.9) \times 10^{-3} \)               | \( (2.5 \pm 0.2) \times 10^{-3} \)               |
| ARGUS     | \( (1.2 \pm 0.9) \times 10^{-3} \)               | \( (2.8 \pm 1.3) \times 10^{-4} \)               |
| CLEO      | \( (1.1 \pm 0.4) \times 10^{-2} \times (1.0 \pm 0.8) \times 10^{-4} \) |

where \( |p| = \sqrt{m_D^2 - (m_P + m_{f_0})^2} \left[ m_D^2 - (m_P - m_{f_0})^2 \right]/2m_D \) is the c.m. momentum of the decay particles. The transition form factor \( F_0^{D \to f_0}(m_P^2) \) is related to the \( + \) and \( - \) components of the pseudoscalar \( (P) \) to scalar \( (S) \) weak-hadronic matrix element defined as \( (p_1 \) is the initial and \( p_2 \) the final momentum and \( q = p_1 - p_2 \)

\[
\langle S(p_2)|J^\mu|P(p_1)\rangle = (p_1 + p_2)^\mu F_+(q^2) + (p_1 - p_2)^\mu F_-(q^2), \quad J^\mu = \bar{q}\gamma^\mu(1 - \gamma^5)c, \quad (3)
\]

by the expression

\[
F_0(q^2) = F_+(q^2) + \frac{q^2}{M_1^2 - M_2^2} F_-(q^2). \quad (4)
\]

In our case \( M_1 \) and \( M_2 \) are the masses of the \( D \)- and \( f_0(980) \)-mesons, respectively. As mentioned, computation of the \( F_+(q^2) \) and \( F_-(q^2) \) requires the knowledge of the \( f_0(980) \) wavefunction. In Ref. [1], the \( f_0(980) \) was taken to be a \( \bar{q}q \) state with a non-strange and a strange component which implies a mixing angle. Higher Fock states were not included. The \( f_0(980) \) wavefunction then reads

\[
\Psi_{f_0} = \frac{1}{\sqrt{2}} \left( |\bar{u}u| + |\bar{d}d| \right) \sin \theta_m + |\bar{s}s| \cos \theta_m = \Phi^u \sin \theta_m + \Phi^s \cos \theta_m, \quad (5)
\]

where \( \theta_m \) is the mixing angle and \( n = u(d) \) or \( s \). The spatial component \( \Phi^u \) and \( \Phi^s \) of the wavefunction are of Gaussian form \( \Phi^{n,s} \propto \exp(-4\alpha_{n,s} k^2/\mu^2) \), where \( k \) is the modulus of the center-of-mass quark momentum and \( \mu = m_q m_{\bar{q}} / (m_q + m_{\bar{q}}) = m_{n,s}/2 \) is the reduced mass of the \( \bar{q}q \) pair. The size parameters \( \alpha_{n,s} \) are then fitted via the transition form factor \( F_0^{D \to f_0} \) in the decay rates Eq. (2) to the experimental branching ratios listed in Table I. The mixing angle \( \theta_m \) has been estimated from \( D_s^+ \to f_0(980)\pi^+ \) and \( D_s^+ \to \phi\pi^+ \) decays to
cover the rather wide range $20^\circ \lesssim \theta \lesssim 40^\circ$ and $140^\circ \lesssim \theta \lesssim 160^\circ$. There are two solutions for $\theta_m$ since the mixing angle enters quadratically into the decay rate formula. We choose to determine the mixing angle ourselves and thus include $\theta_m$ along with $\alpha_n$ and $\alpha_s$ as a parameter, which we determine by fitting the experimental values in Table 1.

3. CONCLUSION

In our effort to model covariant transition form factors for $B \to f_0(980)$ and $D \to f_0(980)$, we have used non-leptonic three-body $D$ decays to fix the parameters $\alpha_n$, $\alpha_s$ and $\theta_m$ of the scalar meson wavefunction. We emphasize that our results are strongly dependent on the $B(f_0 \to \pi^+\pi^-)$ and $B(f_0 \to K^+K^-)$ fractions and that the uncertainties of the experimental branching ratios are large (see Table 1). Therefore, due to the lack of precision and the need for more data, these uncertainties yield large parametric correlations and sizable parameter errors. We hope that newer analyses of three-body $D$-decays with higher statistics will remedy this problem. Definite results for $\alpha_n, \alpha_s$ and $\theta_m$ as well as $B \to f_0(980)$ and $D \to f_0(980)$ transition form factor predictions for space- and time-like momenta will be communicated promptly.

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