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Scalar Mesons in D and B Decays

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The decays of D and B mesons provide new insights into the nature of light scalar mesons. Several recent measurements are presented.

1. Introduction

The light scalar mesons ($J^P = 0^+$) present a challenge for non-perturbative QCD and an opportunity for the understanding of the QCD vacuum. Experimentally they are observed as broad states which heavily overlap and in many production modes are hidden under the tensor mesons [1]. Because their angular distribution is featureless they are often difficult to distinguish from phase space. Today there are too many states observed and their masses are severely shifted compared to other J^P meson states which makes an unambiguous assignment as $^3P_0$ states difficult. It is widely recognized that the scalar mesons are likely to be mixtures of bare quark-antiquark, multiquark states, and glue (glueballs):

$$| >= a|\bar{n}n > +b|\bar{s}s > +c|\bar{q}q\bar{q}q > +d|glue > +..(1)$$

As a result in particle decays the quark content is obscured. To resolve the scalar puzzle information from the production and decay in many modes is needed. In that respect, the decays of D, D_S, and B mesons have several advantages:

- The initial state is a single isolated particle with defined angular momentum $J_B, J_D = 0$, $J_{D_S} = 1$, and a limited number of partial waves contribute.
- The operators for the decay have simple Lorentz- and flavor structure.
- The short range QCD properties are better understood. The weak decay defines the initial quark structure and limits possible transitions (e.g. $\Delta I = \frac{1}{2}$ rule).
- The large variety of transitions to different flavor and spin states with large mass differences in the constituent quarks allows to perform combined and coupled channel analyzes and to use isospin relations to extract initial and final state couplings.
- In semileptonic decays a true spectator approach can be applied and form factors can be measured.

Due to the frequent appearance of scalar mesons in B meson decays their branching ratios and features have to be established in order to extract CP violation in partial waves of opposite CP without dilution. On the other hand, gluonic penguin decays into scalar mesons can add to the search for physics beyond the Standard Model. The determination of hadronic phases in the D-decay Dalitz plot that is dominated by scalar partial waves allows to resolve ambiguities in the measurement of the CP angle γ in the reaction $B \to DK$.
Information discussed here comes from the experiments:

E791	π^-(500 GeV) [Pt, C] $\to$ charm	
FOCUS	γ(Bremsstrahlung) [Be] $\to$ charm	
CLEO-c	$e^+e^- \to \psi(3S) \to \bar{D}D$	
BaBar	$e^+e^- \to \bar{q}q$	@ $\Upsilon(4S)$
Belle	$e^+e^- \to \bar{q}q$	@ $\Upsilon(4S), \Upsilon(5S)$

The latter two are at the B-factories at SLAC and KEK, respectively, and are scheduled to take data at least through 2008. Due to the cross section for $\bar{c}c$ production, $\sigma(e^+e^- \to \bar{c}c) \simeq 1.3$ nb, and the large accumulated data set BaBar and

Belle are practically also charm factories: in Summer'06 both will accumulate more than 1 million events of the type $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ and its charge conjugated reaction. The E791 and FOCUS experiment are terminated and have about 35,400 and 120,000 events of that kind, respectively. CLEO-c finds about 51,700 $D^0 \to K^-\pi^+$ decays in their present sample. The B-factories have taken more than 400 million $\bar{B}B$ pairs with an increasing instantaneous luminosity that today corresponds to more than 10 $\bar{B}B$/s.

Most of the information about scalar mesons is extracted from 3-body decays, where in addition to the invariant mass distribution in two-body subsystems and angular distributions characteristic interference patterns with other partial waves, e.g. with P-waves, can be exploit. For the analysis dominance by 2-body intermediate interactions is usually assumed (Isobar model). Because of the strong overlap and the opening of several decay channels in their vicinity light scalar mesons are typically not described by an ordinary Breit-Wigner resonance formula. In general, the reaction amplitude has to be Lorentz-invariant, analytic, in the absence of 3-body interactions to maintain 2-body unitarity, and other requirements such as isospin invariance in pure hadronic interactions.

The K-matrix formalism is a convenient approximation for the dynamical function of the transition amplitude. It has been applicable to a wide range of hadronic interactions and their coupled channel analysis [2]. It supports the picture of successive quasi-twobody interactions. The formulation of the amplitude for the production (3-body decay) process starts from a corresponding scattering amplitude where unitarity strictly applies. The initial state coupling is substituted with a production strength and phase, transforming the $n \times n$ K-matrix for n open channels into a n-column P-vector, and correspondingly the reaction matrix T into a production amplitude vector F:

$$T = (1 - iK\rho)^{-1}K \;\to\; F = (1 - iK\rho)^{-1}P\,. \quad (2)$$

The ρ is the 2-body invariant phase space matrix for the n different channels. The form $(1-iK\rho)^{-1}$ can be interpreted as resonance propagator with 2-body re-scattering. For a well isolated resonance far from thresholds a natural ansatz for K is $K = g^2/(m^2 - m_0^2)$, with g the (energy dependent) decay coupling, and for $P = \beta g/(m^2 - m_0^2)$, with β the complex production strength, leading to the relativistic Breit-Wigner formula. Only in that simple case one expects the pole position in K to coincide with the pole position of the amplitude (S-matrix) in the complex energy plane. The latter provides the model-independent resonance mass and width (residue), while the K-matrix at first is a parameterization tool. In some models though the m_0 are interpreted as mass of the bare or so called unitarized states [1].

The production amplitude can also be described as $F = QT$ (Q-vector approach) where Q is a slow varying function of the center-of-mass energy and contains no singularities. According to the Watson theorem [3] T and F have the same phase motion below the first inelastic threshold if re-scattering with the third particle is negligible. The amplitude for 2-body scattering with low momentum pions vanishes at a point near threshold defined by the Adler condition [4]. This behavior may not transfer to the associated production process.

2. Isovectors

The candidates are the well established $a_0(980)$ and the $a_0(1450)$. There is no direct access to $a_0(1450)$ in D-decays due to the limited phase space. Production of isovector scalar mesons is suppressed in B-decays as discussed below. The $a_0(980)$ resides next or below the $\bar{K}K$ threshold. This is taken into account by parameterizing the amplitude with the famous Flatté formula, which follows from the choice of a 2×2 K-matrix with $\pi\eta$ and $\bar{K}K$ as relevant channels. The couplings have been established e.g. from coupled channel analyzes in $\bar{p}p$ annihilation [5] or less significant the relative coupling with line-shape measurements.

In 91.5 fb^{-}1 of data taken near the $\Upsilon(4S)$ resonance starting from $D^{*+} \to D^0\pi^+$ decays the BaBar collaboration finds about 92,900 events in the $D^0 \to K_S^0\pi^+\pi^-$, and 13,536 events in the $D^0 \to K_S^0K^+K^-$ Dalitz plot with reconstruction

efficiencies of 18% and 12%, respectively. The D^0 signal has a purity of 97.3%, and its observed width is around 5 MeV/c^2. The acceptance is flat over most of the phase space and the average mass resolution is about 1.1 MeV/c^2. The final state $K_S^0\pi^+\pi^-$ is dominated by $K^*(892)$, $f_0(980)$, and $\rho(770)$. A moment analysis is applied to $K_S^0K^+K^-$ which is dominated by S and P-waves, only. The S-wave ($a_0(980)/f_0(980)$) is described with the Flatté formula using Crystal Barrel parameters [5] for mass and the $\pi\eta$ coupling. The value of the $\bar{K}K$ coupling, $g_{\bar{K}K} = 473\pm49\,\mathrm{MeV}^{\frac{1}{2}}$, turns out to be somewhat larger than the one from Crystal Barrel, $g_{\bar{K}K} = 329\pm27\,\mathrm{MeV}^{\frac{1}{2}}$. The partial wave analysis of the Dalitz plot also requires a 3% contribution to describe a higher mass resonance tail. The analysis assumes the presence of $f_0(1400)$; a uniform non-resonant contribution worsens the quality of the fit. Nevertheless, the K^+K^- system has isospin $I = 0$ and $I = 1$, where for the latter $a_0(1450)$ is a candidate. The $f_0(980)$ contribution in the $a_0(980)$ region is negligible as is demonstrated by comparing the K^+K^- invariant mass distribution with the one for $\bar{K}^0K^+$ ($I = 1$) after normalization to the same phase space area. Another input is the relative small $f_0(980)$ contribution of 5.5% in $D^0 \to K_S^0\pi^+\pi^-$. To determine the relative $\bar{K}K/\pi\eta$ coupling from D-decays a coupled channel analysis with $D \to K\pi\eta$ will be useful. CLEO-c has reconstructed 155 ± 22 events in the D^0 final state $K_S^0\pi^0\eta$ from about 9 fb^{-1} of data [6]. Their analysis finds that the main contribution is $a_0(980)K_S^0$ (fraction=$1.19 \pm 0.09 \pm 0.20 \pm 0.16$). Other resonant contributions are $a_2(1320)K_S^0$, $K^*(892)\eta$, and $K^*(1430)\eta$.

With the assumption that a_0 is a simple $\bar{q}q$ state (or close), $a_0\pi$ and a_0K decays of the B meson are CKM suppressed ($\propto V_{ub}$) tree diagrams [7]. The least suppressed transition is $B \to a_0K$ via gluonic penguin amplitudes ($\propto V_{ts}$). All transitions diagrams where the recoil π or K contains a spectator quark are G-parity suppressed [8]. An analysis of the effective Hamiltonian [9] shows that even the dominant penguins are suppressed by another factor of three or more in amplitude in contrast to the corresponding pseudo-scalar decays such as $K\pi$. Since a_0 is an isovector singlet diagrams cannot contribute. In 82 fb^{-1} BaBar finds upper limits of $7.8\cdot10^{-6}$ and lower at a 90% C.L. for several such decays [10].

3. $I = 1/2$ Scalar Mesons

The $K^*(1430)$ is probably the best established scalar meson candidate. In recent years new data from BES [11] and E791 [12] created controversy about the existence of the lower mass state $\kappa(800)$ in the same $I = \frac{1}{2}$ $K\pi$ S-wave. Most of the information about the $K\pi$ scattering comes from the LASS experiment (SLAC E135) [13] which measured the reactions $K^-p \to K^-\pi^+n$ and $K^-p \to K^0\pi^-p$. Together with results on $K^-\pi^- \to K^-\pi^-$ [14] the LASS group extracted the phase shift δ^I for isospin $I = \frac{1}{2}$ and $I = \frac{3}{2}$ in the mass region above 825 MeV/c^2. The low energy behaviour of the amplitude was parameterized with an effective range expansion:

$$q \cdot \cot\delta = 1/a + bq^2/2\,, \tag{3}$$

with δ the scattering phase, a the scattering length, b the effective range, and q the $K\pi$ breakup momentum. With the identification $K^{-1} = 2q\cdot\cot\delta/m$ the amplitude can be extended to incorporate a pole for $K^*(1430)$ and higher as may be necessary for its parameterization in B-decays ($K = (am)/(2+abq^2)+g_0^2/(m^2-m_0^2)+..$). This ansatz describes scattering on a potential and a and b are predicted by chiral perturbation theory (ChPT) [15]. Therefore, the amplitude does not take left hand cuts into account explicitely. In a formulation with meson exchange in the t- (ρ) and u-channel (K^*), only the $K^*(1430)$ appears as s-pole [16]. The same is true for the above K-matrix approaches. A recent analysis [17] describes the $K\pi$ LASS data in agreement with ChPT. The $I = \frac{3}{2}$ component does not exhibit resonant behaviour and is negligible in the above reactions.

FOCUS has observed a 15% forward-backward asymmetry in the $K\pi$ rest frame with 27,000 reconstructed events of the decay $D^+ \to (K^-\pi^+)\mu^+\nu_\mu$ [18] caused by the interference of $K\pi$ S- and P-wave ($K^*(892)$). The hadronic

phase of 45° near the $K^*(892)$ pole is in agreement with LASS, which is expected since the leptons are true spectators. Furthermore, no resonant behaviour is observed below $K^*(892)$. The LASS wave also fits the $K\pi$ system in the weak $b \to c\bar{c}s$ process $B \to J/\psi K\pi$ as measured by BaBar [19]. However, in weak decays the $I = \frac{1}{2}$ component may not dominate the $I = \frac{3}{2}$ component. Furthermore, the W can internally convert into hadrons violating the spectator assumption and the two isospin components in $K\pi$ can have different magnitudes as compared to wholly hadronic reactions. The $D^+ \to K^-\pi^+\pi^+$ is such a decay. It has been analyzed with Breit-Wigner forms in E791 [12]. Only the introduction of a low-mass κ state yields a satisfactory description of the Dalitz plot.

The $K\pi$ S-wave was also extracted from the same data with an energy-independent approach [20] utilizing the $K^*(892)$ and $K_2^*(1430)$ resonances as interferometers. The resulting $K\pi$ S-wave amplitude differs from the LASS one (phase motion offset is -75° at 0.8 GeV/c^2). Ref. [17] uses a Q-vector approach to parameterize the D-decay amplitude, where the T_{11} component is taken from LASS, assuming Watson's theorem applies in each isospin component separately below the $K\eta'$ threshold (elastic region). As a result, above 1.1 GeV/c^2 the $I = \frac{3}{2}$ component contributes more than 50% of the $I = \frac{1}{2}$. Due to the absence of Adler zeros both components grow towards the $K\pi$ threshold. However, increased statistics is needed to deduce significantly wether a κ pole is needed.

4. Isoscalars

Similar to the $\kappa(800)$ the $\sigma(500)$ experienced a revival due to several new models and observations, and it is also of interest for ChPT [21]. In the analysis of the $D^+ \to \pi^-\pi^+\pi^+$ decay Dalitz plot the E791 experiment [22] requires a resonance at 478 MeV with a width of 324 MeV, where the dynamics is parameterized exclusively with Breit-Wigner forms. The FOCUS experiment [23] uses a K-matrix approach, and for the $\pi\pi$ S-wave an amplitude from a coupled channel analysis to a variety of data sets [24], where no explicit σ-pole is present. Recently, the phase shift below 0.9 GeV has been extracted bin-by-bin from the E791 data using $f_2(1270)$ as interferometer. It is consistent with previous findings.

There are several $\pi\pi$ S-wave parameterizations based on K-matrices available: with 4 K-matrix poles and 2 resonances [25] finds $f_0(980)$ at $(988 - i23)$ MeV, and 5 poles and 5 resonances with $f_0980)$ at $(1024 - i43)$ MeV and somewhat larger width [24], and 4 poles and 4 resonances including a low mass pole [26]. A formulation with t (u) channel ρ (f_2) exchange which also considers the $I = 2$ $\pi\pi$ S-wave does not need a σ [27]. Similar to the flavor-tag decay $J/\psi \to \phi\pi\pi$ the $f_0(980)$ is observed as positive structure in $D_S^+ \to \pi^+\pi^-\pi^+$ (no low mass enhancement) hinting that the primary quark content in this reaction is $\bar{s}s$. Both E791 [28] and FOCUS [23] find that the $\pi\pi$ S-wave contributes about 90% to that decay.

Recently, charmless 3-body B-decays to an odd number of kaons have become important in the search for physics beyond the Standard Model since they are dominated by gluonic penguin transitions. But due to the large phase space and the limited number of events (typically less than 10 events per fb^{-1} compared to D with more than 100 events per fb^{-1}) the full Dalitz plot analysis is at the feasibility limit. On the other hand e.g. the $\pi\pi$ ($\bar{K}K$) S-wave appears rather structureless analoguous to D_S decays. In the $K^+K^-K_S^0$ and $K^+K^-K^+$ final states in addition to $f_0(980)$ a positive resonant structure at a mass of 1500 MeV, called $X(1500)$, is observed [29]. A large fraction of the phase space seems to be occupied by non-resonant S-wave with excess towards threshold, for which only phenomenological models are tested so far [30]. Its nature is not yet understood. The bump at 1500 MeV with a large coupling to $\bar{K}K$ is not straight forwardly identified with the $f_0(1500)$. It is suggested that $f_0(1500)$ interferes with the aferiomentioned S-wave background constructively in KKK, but destructively in the $K\pi\pi$ final states [31].

5. Summary

Since 40 years the light scalar mesons present a puzzle. Charm production experiments and particularly B factories will provide additional insight, but are still limited in the amount of data. A Super-B factory as e.g. proposed for Frascati, Italy, will be a great source for scalar meson spectroscopy.

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