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Review

New heavy mesons as hadronic molecules

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Abstract

We discuss a possible interpretation of the $D_{s0}^*(2317)$, $D_{s1}(2460)$, $B_{s0}^*(5725)$ and $B_{s1}(5778)$ mesons as hadronic molecules. Using an effective Lagrangian approach we calculate their weak, strong and radiative decays. The new impact of the molecular structure of these states is the presence of $u(d)$ quarks in the K, $D^{(*)}$ and $B^{(*)}$ mesons which gives rise to the direct strong isospin-violating transitions $D_{s0}^*(B_{s0}^*) \to D_s(B_s) + \pi^0$ and $D_{s1}(B_{s1}) \to D_s^*(B_s^*) + \pi^0$ in addition to the modes generated by $\eta - \pi^0$ mixing as was considered before in the literature.

Keywords: Bottom; Charm and strange mesons; Hadronic molecule; Strong and radiative decay; Isospin violation

1. Introduction

Nowadays there is much interest to study newly observed mesons and baryons in the context of a hadronic molecule interpretation [1]. As stressed for example in Ref. [2] the scalar $D_{s0}^*(2317)$ and axial $D_{s1}(2460)$ mesons could be candidates for a scalar DK and an axial D^*K molecule because of a relatively small binding energy of ~50 MeV. These states were discovered and confirmed just a few years ago by the Collaborations BABAR at SLAC, CLEO at CESR and Belle at KEKB [3]. In the interpretation of these experiments it was suggested that the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons are the P-wave charm-strange quark states with spin–parity quantum numbers $J^P = 0^+$ and $J^P = 1^+$, respectively.

The next important question concerns the possible structure of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons. The simplest interpretation of these states is that they are the missing $j_s = 1/2$ (j_s is the angular momentum of the s-quark) members of the $c\bar{s}$ $L = 1$ multiplet. However, this standard quark model scenario is in disagreement with experimental observation, since the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ states are narrower and their masses are lower when compared to theoretical predictions (see e.g. discussion in Ref. [1]). Therefore, in addition to the standard quark–antiquark picture alternative interpretations of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons have been suggested: four-quark states, mixing of two- and four-quark states, two-diquark states and two-meson molecular states. Up to now strong and radiative decays of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons have been calculated using different approaches [4–26]: quark models, effective Lagrangian approaches, QCD sum rules, lattice QCD, etc.

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A new feature related to the molecular $D^{(*)}K$ structure of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons is that the presence of $u(d)$ quarks in the $D^{(*)}$ and K mesons gives rise to direct strong isospin-violating transitions $D_{s0}^* \to D_s\pi^0$ and $D_{s1} \to D_s^*\pi^0$ in addition to the decay mechanism induced by $\eta - \pi^0$ mixing, as considered previously.

In the present paper we will consider the strong, radiative and leptonic decays of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons using an effective Lagrangian approach. The approach is based on the hypothesis that the D_{s0}^* and D_{s1} are bound states of D, K and D^*, K mesons, respectively. In other words, we investigate the position that the D_{s0}^* and D_{s1} are (DK) and (D^*K) hadronic molecules. Their couplings to the constituents are described by effective Lagrangians. The corresponding coupling constants $g_{D_{s0}^*DK}$ and $g_{D_{s1}D^*K}$ are determined by the compositeness condition $Z = 0$ [27,28], which implies that the renormalization constant of the hadron wavefunction is set equal to zero. Note, that this condition was originally applied to the study of the deuteron as a bound state of proton and neutron [27]. Then it was extensively used in low-energy hadron phenomenology as the master equation for the treatment of mesons and baryons as bound states of light and heavy constituent quarks (see Refs. [28,29]). Recently the compositeness condition was used to study the light scalar mesons a_0 and f_0 as $K\bar{K}$ molecules [30]. A new impact of the molecular structure of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons is that the presence of $u(d)$ quarks in the D^* and K mesons gives rise to the direct strong isospin-violating transitions $D_{s0}^* \to D_s\pi^0$ and $D_{s1} \to D_s^*\pi^0$ in addition to the decay induced by $\eta - \pi^0$ mixing considered before in the literature. We show that the direct transition dominates over the $\eta - \pi^0$ mixing transitions. The obtained results for the partial decay widths are consistent with previous calculations. We also extend our formalism to the bottom sector, that is to the $B_{s0}^*(5725)$ and $B_{s1}(5778)$ states.

2. Approach: Basic notions and results

In this section we briefly discuss the formalism for the study of hadronic molecules. For example, we consider the $D_{s0}^{*\pm}(2317)$ meson as a bound state of D and K mesons. Extension to other states is straightforward. First of all we specify the quantum numbers of the $D_{s0}^{*\pm}(2317)$ meson. We use the current results for the quantum numbers of isospin, spin and parity: $I(J^P) = 0(0^+)$ and mass $m_{D_{s0}^*} = 2.3173$ GeV [3]. Our framework is based on an effective interaction Lagrangian describing the coupling between the $D_{s0}^*(2317)$ meson and their constituents — D and K mesons:

$$\mathcal{L}_{D_{s0}^*}(x) = g_{D_{s0}^*} D_{s0}^{*-}(x) \int \mathrm{d}y\, \Phi_{D_{s0}^*}(y^2) D(x + w_{KD}y) K(x - w_{DK}y) + \text{H.c.} \quad (1)$$

where D and K are the corresponding meson doublets, $w_{ij} = m_i/(m_i + m_j)$ is a kinematic variable, m_D and m_K are the masses of D and K mesons. The correlation function $\Phi_{D_{s0}^*}$ characterizes the finite size of the $D_{s0}^*(2317)$ meson as a D K bound state and depends on the relative Jacobi coordinate y with x being the center of mass (CM) coordinate. In the numerical calculations we employ the Gaussian form for $\Phi_{D_{s0}^*}$. Its Fourier transform reads as $\tilde{\Phi}_{D_{s0}^*}(p_E^2) = \exp(-p_E^2/\Lambda_{D_{s0}^*}^2)$, where p_E is the Euclidean Jacobi momentum. Here $\Lambda_{D_{s0}^*}$ is a size parameter, which parametrizes the distribution of D and K mesons inside the D_{s0}^* molecule. The coupling constant $g_{D_{s0}^*}$ is determined by the compositeness condition [27,28], which implies that the renormalization constant of the hadron wavefunction is set equal to zero: $Z_{D_{s0}^*} = 1 - \Sigma'_{D_{s0}^*}(m_{D_{s0}^*}^2) = 0$, where $\Sigma'_{D_{s0}^*}$ is the derivative of the D_{s0}^* meson mass operator.

The effective Lagrangian (1) is the starting point for the study of the decays of hadronic molecules. It defines the transition of the molecule into its constituents. Then we should specify the Lagrangian which describes the interaction of the constituents with external fields (hadrons and gauge bosons) and the diagrams which contribute to the matrix elements of physical processes. All further details can be found in Refs. [21–24].

3. Results

Below, in Tables 1–4, we display our results for the strong $\Gamma(D_{s0}^*(D_{s1}) \to D_s(D_s^*)\pi)$ and radiative $D_{s0}^*(D_{s1}) \to D_s^*(D_s)\gamma$decay widths and their ratios $R_{D_{s0}^*} = \Gamma(D_{s0}^* \to D_s^*\gamma)/\Gamma(D_{s0}^* \to D_s\pi)$ and $R_{D_{s1}} = \Gamma(D_{s1} \to D_s\gamma)/\Gamma(D_{s1} \to D_s^*\pi)$, including the extension to the bottom sector, and compare them with the predictions of other approaches.