HEAVY MESON MASSES AND DECAY CONSTANTS

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ABSTRACT

Masses and decay constants of mesons containing a single c or b quark are described within the framework of heavy-quark symmetry. The $B^*_s - B_s$ and $B^{*0} - B^0$ mass splittings are found equal to within a fraction of an MeV. Decay constants of $D$ and $B$ mesons are estimated using isospin mass splittings in the $D$, $D^*$, $B$, and $B^*$ states to isolate the electromagnetic hyperfine interaction between quarks. A relation following from the use of splittings in kaons is also considered.

1. Introduction

Mesons containing one heavy quark ($c, b$) are of fundamental importance for the understanding of the strong interactions, since they consist of a single light quark bound to a nearly static source of color. We describe here some recent work on the masses [1] and decay constants [2] of such mesons.

Results on heavy meson masses come from an expansion to first order in $\alpha$, first order in light-quark masses ($m_u, m_d, m_s$), and first order in $1/m_Q$, where $Q$ is a heavy quark. We predict one new relation: The photons in $B^*_s \to B_s \gamma$ and $B^{*0} \to B^0 \gamma$ should have equal energies.

Decay constants of heavy mesons are crucial for interpreting data on particle-antiparticle mixing in the neutral $B$ meson system, and for anticipating and interpreting new signatures for CP violation. We describe a method for determination of these constants which relies on the isospin splittings of the $D$, $D^*$, $B$, and $B^*$ mesons. We also consider a relation following from the use of splittings in kaons. The isospin splittings allow one to extract the contributions of the spin-dependent electromagnetic interaction between light and heavy quarks. Additional assumptions about quark masses are required in order to interpret these contributions in terms of decay constants.

2. Masses of $D$ and $B$ mesons

The most general mass operator containing contributions of first order in (a) light quark masses $m_q$, (b) electromagnetic interactions, and (c) $1/m_Q$, including terms of order $m_q/m_Q$ and $\alpha/m_Q$, contains 11 terms, not counting ones which can be absorbed into heavy quark masses [1]. One result of this expansion is the familiar

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relation between the strong hyperfine splitting between the $^3S_1$ and $^1S_0$ $D$ and $B$ states, which says that $\Delta M^2$ should be approximately the same for the two systems. Aside from this result, we find one new prediction:

$$[B_s^* - B_s] - [\bar{B}^0 - \bar{B}^0] = (m_c/m_b)([D_s^* - D_s] - [D^{*+} - D^+]) ,$$

where here and below symbols stand for particle masses. Since $D_s^* - D_s = 141.5 \pm 1.9$ MeV [3] and $D^{*+} - D^+ = 140.64 \pm 0.08 \pm 0.06$ MeV [4], we expect the right-hand side of this relation to be about $0.3 \pm 0.6$ MeV. A recent study suggests that the smallness of the result could be due to accidental cancellation, and that there could be additional contributions of up to a few MeV from effects of higher order in $1/m_Q$ [5].

3. Predictions for decay constants

In the nonrelativistic formula

$$f_M^2 = \frac{12|\Psi(0)|^2}{M_M^2}$$

we seek an estimate of $\Psi(0)$, the nonrelativistic wave function at zero separation of the light and heavy quark. This may be obtained in a constituent quark model from the contribution of electromagnetic hyperfine splitting to meson masses. Specifically, in the limit in which the wave functions of a light quark bound to a $c$ and $b$ quark are the same,

$$\Delta(D) \equiv (D^{+} - D^{0}) - (D^{*+} - D^{*0}) = a + \frac{8\pi\alpha_Qc}{3m_um_c}|\Psi(0)|^2 ,$$

$$\Delta(B) \equiv (\bar{B}^0 - B^-) - (\bar{B}^{*0} - B^{*-}) = \frac{m_c}{m_b} + \frac{8\pi\alpha_Qb}{3m_um_b}|\Psi(0)|^2 .$$

(3)

(4)

Here $a$ denotes the effects of $m_u \neq m_d$ in the color hyperfine interaction and of spin-dependent light-quark electromagnetic self-energies. Now, while we know [4] that $\Delta(D) = 4.80\pm0.11$ MeV, the corresponding value [6] for $B$ mesons, $\Delta(B) = 0.12\pm0.58$ MeV, is too poorly known to allow us to separate the effects of $a$ and $|\Psi(0)|^2$. In Fig. 1 we show the dependence of predicted decay constants on $\Delta(B)$.

In order to proceed further we use a trick motivated by a result of Cohen and Lipkin [8] which appeals to the similarity between the kaon and $B$ systems. We define

$$\Sigma(B) \equiv (\bar{B}^{*0} + B^{*-}) - (\bar{B}^0 + B^-) ,$$

with similar definitions [cf. (4)] for $\Delta(K)$ and $\Sigma(K)$. We then estimate

$$\Delta(B) = \Delta(K)\Sigma(B)/\Sigma(K) = (-0.06 \pm 0.04) \text{ MeV} .$$

(6)

As a result, we can separate out the electromagnetic hyperfine term in (2) and (3), finding

$$|\Psi(0)|^2 = (13.8 \pm 1.4) \times 10^{-3} \text{ GeV}^3 , \quad f_D^{(0)} = (290 \pm 15) \text{ MeV} , \quad f_B^{(0)} = (177 \pm 9) \text{ MeV} .$$

(7)
4. Comparison with experiment

The Mark III Collaboration finds $B(D \to \mu \nu) \times 10^{-4}$ (90% c.l.), corresponding to $f_D < 290$ MeV. The lowest-order result (7) obtained suggests that $f_D$ may be close to its present upper limit, so a search for $D \to \mu \nu$ (e.g., through the reaction $e^+e^- \to \psi(3770) \to D^+D^-$ at the Beijing Electron Synchrotron) should prove fruitful.

It may be possible, for example at CLEO, to look for the decay $D \to \mu \nu$ by tagging a $D^\pm$ using the reaction $D^{*\pm} \to \pi^0 D^\pm$, since the $\pi^0$ is very soft in the $D^*$ or $D$ center-of-mass system, and helps to label the frame of the decaying $D$. The signal will show up in a characteristic band of $m(\pi^0\mu)$. One will probably need additional kinematic information to reduce backgrounds (e.g., from semileptonic decays).
Recent evidence for the reaction $D_s \to \mu \nu$ in emulsion [9] rests on the observation of a muon beyond the kinematic endpoint for semileptonic decays of $D^+$ and $D_s$. A search for $D_s \to \mu \nu$ using the information from the photon in $D_s^* \to D_s \gamma$ is possible in principle [10]. One needs additional jet or missing energy information.

The WA75 result [9], $f_{D_s} = 232\pm 69$ MeV (based on 7 events above background) may be used indirectly to estimate corrections of order $1/m_Q$ to the lowest-order formula (2). First we estimate $|\Psi(0)|^2_D$ using the approximate equality of strong hyperfine splittings in the $D$ and $D_s$ systems, which implies that

$$|\Psi(0)|^2_D/m_u m_c = |\Psi(0)|^2_{D_s}/m_s m_c.$$  

With $m_u/m_s = 310$ MeV/485 MeV, we then estimate from the observed value of $f_{D_s}$ that $f_D = 190\pm 57$ MeV. If the discrepancy with our lowest-order prediction is ascribed to $1/m_Q$ corrections, we may write $f_D = f_D^{(0)}(1 - [\Delta/m_D])$, implying $\Delta/m_D = 0.35\pm 0.20$ and hence $\Delta/m_B = 0.13\pm 0.07$ or $f_B = f_B^{(0)}(1 - [\Delta/m_B]) = (154\pm 17)$ MeV. QCD corrections probably raise this value by about 10%. The most recent range of lattice gauge theory values quoted at this conference [11] puts $f_B$ in the range between 175 and 200 MeV and $f_D$ just slightly above 200 MeV. A value of $f_B$ of about 170 MeV is entirely compatible with recent fits to parameters of the Cabibbo-Kobayashi-Maskawa matrix and $B - \bar{B}$ mixing data.

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