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POSITIVE AND NEGATIVE PARITY CHARMED MESONS IN HEAVY HADRON CHIRAL PERTURBATION THEORY

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Abstract

Using heavy hadron chiral perturbation theory (HHχPT), we present (to order Q^3) the masses, strong decays, and electromagnetic decays of the lowest lying even and odd parity charmed mesons. Here, $Q \sim \Lambda_{QCD}/m_c, m_\pi/\Lambda_\chi$. We find: the unusually low masses of the positive parity charmed strange states are consistent with reasonably sized HHχPT parameters; the parity-doubling model parameters are RG stable in HHχPT; and the positive parity charmed strange states are unlikely to be "molecular" bound states of lower mass mesons. We present some typical fit parameters.

1 Introduction

The relevant portion of the charmed meson spectrum is shown in Fig. 1 [1]. The important points to notice from this figure are: (a) the positive parity (0,1) pair have the same ($\sim$140 MeV) hyperfine splitting as the negative parity (0,1) pair. This is not required by QCD. It could be an accident, or it could be evidence in favor of the so-called parity doubling model [2]. (b) The positive parity charmed-strange states exist at unexpectedly low energies. Related to this may be (c) the unusually small ($\sim$10 MeV) SU(3) breaking, when it is expected to be $\sim$100 MeV (as it is elsewhere in this spectrum), and the narrowness of the even parity charmed-strange states. Were the $D_{s0}(D'_{s1})$ heavy enough to decay to a $D(D^*)$ and a kaon, they would be as broad as their non-strange partners. Instead, they decay through an isospin violating channel.

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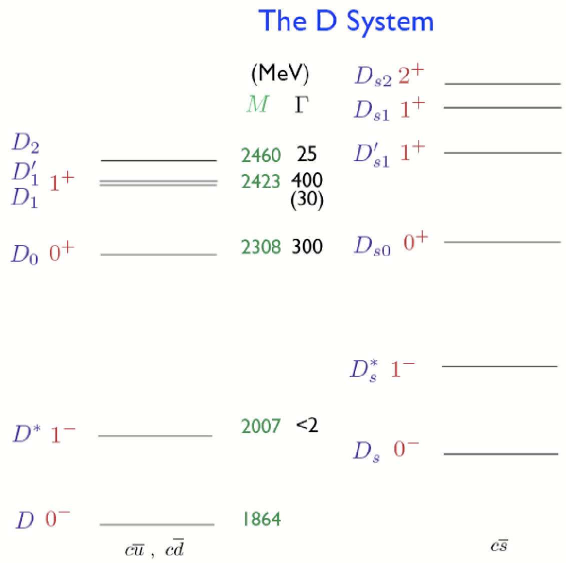

Figure 1: The lowest masses in the charmed meson spectrum [1]

2 Heavy Hadron Chiral Perturbation Theory for the $(0^-, 1^-)$ and $(0^+, 1^+)$ charmed mesons

We wish to determine whether these unexpected characteristics of the charmed mesons are consistent with Heavy Hadron Chiral Perturbation Theory (HHχPT) [3]. HHχPT incorporates two limits of QCD where there exist enhanced symmetries. If we live in a world that is perturbatively close to these limits, then operators in the HHχPT Lagrangian can be categorized by how large we expect them to be in this perturbative expansion. In the limit that the up, down, and strange quark masses are taken to zero, QCD exhibits a chiral symmetry. The octet of pions, kaons, and eta are taken to be the pseudo-Goldstone bosons of this spontaneously broken symmetry. Explicit breaking is included as an expansion in m_π/Λ_χ, where $\Lambda_\chi \sim 1$ GeV is the chiral symmetry breaking scale. In the limit that the charm (and bottom) quark masses are taken to infinity, QCD exhibits a heavy quark spin-flavor symmetry. Corrections to this appear as an expansion in $1/m_Q$, where m_Q is the charm or bottom quark mass. So long as momentum transfers in the problem are "small" compared to Λ_χ and m_Q, the theory should be predictive.

Heavy quark spin-flavor symmetry is made manifest by redefining the heavy quark field to make it explicitly velocity-dependent. The effect is to remove the portion of the heavy quark's momentum that is not relevant to the process being considered. After that redefinition, derivatives of the heavy quark fields will yield only the off-shell momentum small compared to m_Q and not include $m_Q v$ factors that would spoil the perturbative expansion [3]:

$$\mathcal{L}_{QCD}^{heavy} = \overline{Q}(i\not{D} - m_Q)Q \rightarrow \overline{h}_v^{(Q)} iv.D h_v^{(Q)} \ , \tag{1}$$

where $Q = e^{-im_Q v.x}(h_v^{(Q)} + \xi_v^{(Q)})$ and $\xi_v^{(Q)}$ is the "small" component of the heavy quark spinor when $p_Q^\mu = m_Q v^\mu + k^\mu$.

Invoking this symmetry in the hadron language, the heavy meson multiplets are contained in [3, 4]:

$$H_a = \frac{1+\not{v}}{2}[P_a^{*\mu}\gamma_\mu - P_a\gamma_5] \ , \tag{2}$$

$$S_a = \frac{1+\not{v}}{2}[\mathcal{P}_a^{*\mu}\gamma_\mu\gamma_5 - \mathcal{P}_a] \ , \tag{3}$$

where $P_a \sim (D^{0,+}, D_s)$ and $P_a^{*\mu} \sim (D^{*(0,+)}, D_s^*)$ contain the odd parity multiplet (a is the flavor label of the light quark) and $\mathcal{P}_a \sim (D_0^{(0,+)}, D_{s0})$ and $\mathcal{P}_a^{*\mu} \sim (D_1'^{(0,+)}, D_{s1}')$ contain the even parity multiplet.

The leading order kinetic and strong interaction terms are contained in [5]

$$\begin{aligned} \mathcal{L}_{axial} \ = \ & -\mathrm{Tr}[\overline{H}_a(iv.D_{ab} - \delta_H)H_b] + Tr[\overline{S}_a(iv.D_{ab} - \delta_S)S_b] \\ & + g\,\mathrm{Tr}[\overline{H}_a H_b \not{A}_{ba}\gamma_5] \ + \ g'\,\mathrm{Tr}[\overline{S}_a S_b \not{A}_{ba}\gamma_5] \\ & + h\ (\mathrm{Tr}[\overline{H}_a S_b \not{A}_{ba}\gamma_5] + h.c.) \end{aligned} \tag{4}$$

where the pion, kaon, and η fields are in the 3x3 matrix M, $\xi = e^{iM/f}$, $D^\mu = \partial^\mu + V^\mu$, $V^\mu = \frac{1}{2}(\xi\partial^\mu\xi^\dagger + \xi^\dagger\partial^\mu\xi)$, and $A^\mu = \frac{i}{2}(\xi\partial^\mu\xi^\dagger - \xi^\dagger\partial^\mu\xi)$. This portion of the Lagrange density contains a number of unknown parameters. Were we able to solve QCD we could match it to this effective Lagrange density and predict the parameters. Instead, we must rely on either lattice determinations or experimental measurements. The parameters are: g, the coupling between odd-parity heavy mesons and light mesons; g', the coupling between even-parity heavy mesons and light mesons; h, the coupling between an odd-parity meson, an even-parity meson, and light mesons; and $\delta_S - \delta_H$, the shift between the center of mass of the even-parity and odd-parity heavy mesons.

The mass terms appear in [6, 7]

$$
\begin{aligned}
\mathcal{L}_v^{\rm mass} \;=\; & -\frac{\Delta_H}{8}{\rm Tr}[\overline{H}_a\sigma^{\mu\nu}H_a\sigma_{\mu\nu}]+\frac{\Delta_S}{8}{\rm Tr}[\overline{S}_a\sigma^{\mu\nu}S_a\sigma_{\mu\nu}\ ]\\
&+a_H{\rm Tr}[\overline{H}_aH_b]\,m^\xi_{ba}-a_S{\rm Tr}[\overline{S}_a\ S_b]\,m^\xi_{ba}\\
&+\sigma_H{\rm Tr}[\overline{H}_aH_a]\,m^\xi_{bb}-\sigma_S{\rm Tr}[\overline{S}_aS_a]\,m^\xi_{bb}\\
&-\frac{\Delta_H^{(a)}}{8}{\rm Tr}[\overline{H}_a\sigma^{\mu\nu}H_b\sigma_{\mu\nu}]\,m^\xi_{ba}+\frac{\Delta_S^{(a)}}{8}{\rm Tr}[\overline{S}_a\sigma^{\mu\nu}S_b\sigma_{\mu\nu}]\,m^\xi_{ba}\\
&-\frac{\Delta_H^{(\sigma)}}{8}{\rm Tr}[\overline{H}_a\sigma^{\mu\nu}H_a\sigma_{\mu\nu}]\,m^\xi_{bb}\ +\frac{\Delta_S^{(\sigma)}}{8}{\rm Tr}[\overline{S}_a\sigma^{\mu\nu}S_a\sigma_{\mu\nu}]\,m^\xi_{bb}\ , \qquad (5)
\end{aligned}
$$

where $m^\xi_{ba}=\frac{1}{2}(\xi m_q\xi+\xi^\dagger m_q\xi^\dagger)_{ba}$, and $m_q={\rm diag}(m_u,m_d,m_s)$. The unknown parameters here are Δ_H and Δ_S, giving hyperfine splitting; a_H and a_S, $\mathcal{O}(m_q)$ corrections but spin-symmetry preserving; and $\Delta_H^{(a)}, \Delta_S^{(a)}, \Delta_H^{(\sigma)}$, and $\Delta_S^{(\sigma)}$, $\mathcal{O}(m_q)$ and spin-symmetry violating.

Leading order electromagnetic decays are dictated by [8–10]

$$
\begin{aligned}
\mathcal{L} \;=\; & \frac{e\beta}{4}{\rm Tr}[\overline{H}_aH_b\sigma^{\mu\nu}]F_{\mu\nu}Q^\xi_{ba}+\frac{e\tilde{\beta}}{4}{\rm Tr}[\overline{H}_aS_b\sigma^{\mu\nu}]F_{\mu\nu}Q^\xi_{ba}\\
&+\frac{e\beta_s}{4}{\rm Tr}[\overline{S}_aS_b\sigma^{\mu\nu}]F_{\mu\nu}Q^\xi_{ba} \qquad (6)
\end{aligned}
$$

where $Q^\xi_{ba}=\frac{1}{2}(\xi Q\xi^\dagger+\xi^\dagger Q\xi)_{ba}$ and $Q={\rm diag}(2/3,-1/3,-1/3)$.

3 Masses and the Parity Doubling Model

If isospin symmetry is imposed, there are eight independent masses among the even and odd parity multiplets. The non-strange even parity masses have large errors associated with them, and these are the unusually low masses that might challenge HHχPT. At leading order, there are eight parameters and these may be fit to the eight masses. At order Q^3, g, h, and g' also enter. Those expressions are given in Ref. [7].

What can HHχPT say about the viability of the parity doubling model to explain the near equality of the hyperfine splittings within the even and odd parity multiplets? A one-loop renormalization analysis yields the following equations [7]:

$$
\begin{aligned}
&\mu^2\frac{d}{d\mu^2}(\Delta_S-\Delta_H)=\frac{4}{9\pi^2f^2}(g'^2\Delta_S^3-g^2\Delta_H^3)\\
&+\frac{2h^2}{3\pi f^2}(\Delta_S-\Delta_H)*\mathcal{F}[\delta_S-\delta_H,\Delta_S-\Delta_H] \qquad (7)
\end{aligned}
$$

$$\begin{aligned}
\mu\frac{d}{d\mu}(g+g') &= -\frac{9}{4\pi^2 f^2}(\delta_H-\delta_S)(g+g') \\
\mu\frac{d}{d\mu}(g-g') &= -\frac{7}{4\pi^2 f^2}(\delta_H-\delta_S)(g-g') \qquad (8)\\
(m_{S_3^*}-m_{S_3})-(m_{H_3^*}-m_{H_3}) &= \frac{g'^2}{f^2}(\cdots)-\frac{g^2}{f^2}(\cdots)\ , \qquad (9)
\end{aligned}$$

where $\mathcal{F}$ is a (known) function of $(\delta_S-\delta_H)$ and $(\Delta_S-\Delta_H)$ and the $(\cdots)$ in the last equation indicate identical (at this order) expressions. The significance of the above equations is that if at any point in the RG evolution $|g|=|g'|$ and $\Delta_H=\Delta_S$, they remain so; and the mass splitting between S_3^* and S_3 remains the same as the splitting between H_3^* and H_3. This means that, from the point of view of HHχPT, the parity doubling model is stable to one loop.

4 Electromagnetic and Strong Decays

Present values for electromagnetic decays from the even-parity to odd-parity states are [11]:

$$\begin{aligned}
\frac{D_{s0}(2317)\to D_s^*\gamma}{D_{s0}(2317)\to D_s\pi^0} &< 0.059 \\
\frac{D'_{s1}(2460)\to D_s^*\gamma}{D'_{s1}(2460)\to D_s^*\pi^0} &< 0.16 \\
\frac{D'_{s1}(2460)\to D_s\gamma}{D'_{s1}(2460)\to D_s^*\pi^0} &= 0.27 \text{ to } 0.55 \qquad (10)
\end{aligned}$$

With this information, along with data on strong and electromagnetic decays within the odd-parity multiplet and a limit on electromagnetic decay within the even-parity multiplet, we have fit to HHχPT parameters to order Q^3. There are still not enough experiments to constrain these parameters. So all we can say at this point is that the data is consistent with an HHχPT description of the physics. This is important because if the power counting in HHχPT is correct, we expect its predictions to agree with those of QCD. An example of a parameter fit yielding electromagnetic decays at the limit of their experimental values (when only limits are available) is [10]:

$$\begin{gathered}
g\sim 0.5,\ g\sim 0.5,\ h\sim -0.96,\ \frac{h'}{m_c}\sim -0.29,\ g'\sim -0.64\ , \\
\beta\sim 1.5\ \mathrm{GeV}^{-1},\ \beta_s\sim -6\ \mathrm{GeV}^{-1},\ \tilde{\beta}\sim 0.004\ \mathrm{GeV}^{-1},\ \tilde{\beta}'\sim 0.001\ , \qquad (11)
\end{gathered}$$

where h' contributes to the isospin violating decay from $D_{s0}(D'_{s1})$ to $D_s(D_s^*)$, $\tilde{\beta}$ and $\tilde{\beta}'$ come with higher order electromagnetic operators, and those parameters whose values do not significantly affect the result are not shown.

5 Testing the Molecular Hypothesis

One hypothesis for why the D_{s0} and D'_{s1} are found at masses just below threshold to decay to DK and D^*K, respectively, is that they are in fact bound states of these mesons. Mehen and I investigated this possibility by calculating what the electromagnetic decay ratios would be if the $D^{(*)}$ and K were bound nonrelativistically. We did not solve for this bound state, but took the wavefunction components as unknowns. Keeping the expansion to leading order in the three momentum of the constitutents leaves only the wavefunction at the origin, which cancels in the ratio of electromagnetic to strong decays. Even if the errors in the estimate are near 40%, it would be hard to reproduce the experimental measurements/limits with this molecular model. In particular, the dependence of the cross section on the photon energy is E_γ^3 in the HHχPT treatment but only E_γ in the molecular interpretation. Clearly the data favor a strong scaling with E_γ. There are those who disagree with this conclusion [12] so it will be useful to investigate further.

6 The B meson spectrum

One way to increase the amount of experimental information available to fit unknown parameters is to utilize the flavor part of the spin-flavor symmetry of $HH\chi$PT. Further decay information on the b analogues of the even-parity and odd-parity c mesons is expected. In the meantime we have the following mass information [1]:

$$m_{H_1}^{(b)} = 5279 \text{ MeV} \qquad m_{H_1^*}^{(b)} = 5325 \text{ MeV} \tag{12}$$

$$m_{H_3}^{(b)} = 5366 \text{ MeV} \qquad m_{H_3^*}^{(b)} = 5412 \text{ MeV} \tag{13}$$

From HQET operators we know that [13]:

$$\begin{aligned} \overline{m}_S^{(b)} - \overline{m}_H^{(b)} &= \overline{m}_S^{(c)} - \overline{m}_H^{(c)} + \mathcal{O}(1/m_Q) \\ \frac{m_{H^*}^{(b)} - m_H^{(b)}}{m_{H^*}^{(c)} - m_H^{(c)}} = \frac{m_{S^*}^{(b)} - m_S^{(b)}}{m_{S^*}^{(c)} - m_S^{(c)}} &= \frac{m_c}{m_b} + \mathcal{O}(\frac{1}{m_Q}) \ , \end{aligned} \tag{14}$$

where $\overline{m}_{H,S}^{(Q)} = (3m_{H^*,S^*}^{(Q)} + m_{H,S}^{(Q)})/4$ from which we expect, with errors at the ± 30 MeV level: $m_{S_1}^{(b)} = 5709$ MeV, $m_{S_1^*}^{(b)} = 5746$ MeV, $m_{S_3}^{(b)} = 5716$ MeV, and $m^{(b)}_{S^*_3} = 5763$ MeV. Not unexpectedly, this exercise predicts that the even-parity strange-beauty mesons will lie low in mass like their charmed partners. D0 has seen evidence of an excited B_1 mass near 5724 MeV [14].

7 Conclusion

To summarize, we conclude that HHχPT predictions to $\mathcal{O}(Q^3)$ for strong and electromagnetic decays are consistent with the available data, but we need more data to further constrain the unknown parameters. We find the molecular interpretation of the D_{s0} and D'_{s1} to be disfavored given the available electromagnetic decay data. A one loop renormalization group analysis indicates that the parity doubling model is stable. We make predictions for the spectrum of excited B mesons. We look forward to future experimental measurements on both the c and b excited meson systems.

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