HEAVY FLAVOR SPECTROSCOPY

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1. INTRODUCTION

As a useful by-product of the unfolding searches for mixing and CP-violation effects in the beauty sector there will accrue very large data samples for the study of heavy flavor spectroscopy. Interest in this field may be provisionally divided into two general classes:

I Hidden flavor states, i.e. $c\bar{c}$ and $b\bar{b}$ onium states.

II Open flavor states
a) The D, D_s, B, B_s, and B_c meson systems
b) Charm and beauty flavored baryons

In this brief note we emphasize that there are many missing (undiscovered) states in both categories—states which are not readily produced exclusively due to quantum number preferences or states which are not readily observed inclusively due to experimentally difficult decay channels. As recorded luminosities increase it may be possible to fill in some of the holes in the present listings of heavy flavor states. Of particular interest to us would be the identification of heavy flavor mesons which are not easily explained in terms of a $q\bar{q}$ paradigm but rather may be evidence for **hadro-molecular** states.

At Snowmass 1993 the topic of self-tagging schemes in B meson production was very much in vogue. Whether or not excited B-meson flavor-tagging will prove to be competitive with traditional methods based on the partner $\bar{B}$ decay remains to be seen. We suggest however that the richness of the excited B-system may undermine the efficacy of self-tagging schemes.

2. HEAVY FLAVOR ONIUM STATES

Figure 1, the bottomonium spectrum, illustrates several salient features of heavy flavor onium spectroscopy. The observed states, shown in solid lines, consist of six $^3S_1$ and six $^3P_{J=0,1,2}$ states. Conspicuous in their absence are D-wave states, singlet P-wave states, and the $^1S_0$'s. Potential model predictions for some of these states are shown in dashed lines. The reasons for this pattern are well known: much of the world's sample of beauty particles (hidden and open) comes from e^+e^- machines where the $b\bar{b}$ pair has the quantum numbers of the virtual annihilation photon, 1^{--}. Triplet P-wave states are subsequently populated through radiative decays of higher-lying $^3S_1$ states. On the other hand, inclusive production at hadron colliders might lead to a more democratic population of quantum levels. The problem then becomes one of identifying transitions to the ground state through small and experimentally difficult decay modes.

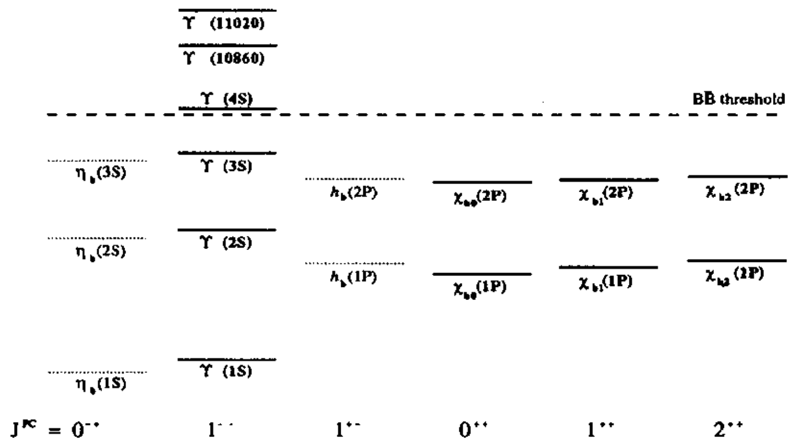

Figure 1. The bottomonium spectrum.

The charmonium spectrum is somewhat better represented in terms of observed states. In contrast to bottomonium there is an established $^1S_0$ (η_c) and there is the recent discovery of the singlet 1^1P_1 (h_c) in a hadro-formation experiment[1]. As anticipated, the observed mass of the h_c is very close to the spin-weighted centroid of the triplet P-wave family. The h_c has also been seen inclusively, again solely in the $J/\psi\pi^0$ decay mode, albeit with lower statistical accuracy[2]. One interesting feature of this decay mode ($J/\psi\pi^0$) is that it violates isospin conservation. This mode also suggests investigating $\Upsilon\pi^0$ final states as a possible signature for the bottomonium $^1P_1$'s.

Generally the spacings between charmonium and bottomonium states are reasonably well described by potential models. Also, independent of the choice of model there appears to be a general scaling in level spacings with quark mass. Thus on the whole potential model predictions should serve as useful guides to undiscovered states.

3. EXCITED HEAVY FLAVOR STATES

A summary of the present understanding of the quark-model assignments for open flavor mesons can be found in the Particle Data Group review[3]. As in the hidden flavor spectra, many slots remain to be experimentally filled. We draw particular attention to the first excited kaon, the $K_1(1270)$ ($J^P = 1^+$). The largest decay branching ratio for this state is into $K\rho$ (42±6%), which can be contrasted with the decay into $K^*(892)\pi$ (16±5%). Why the $K\rho$ mode is so dominant is not readily understood within the quark-antiquark constituent picture. Intriguingly, the central mass of the $K_1(1270)$ is very close to the sum of the central mass of the broad ρ (770) and the K (500 MeV). Also, we note that 1270 MeV is substantially lower than the centroid of the natural triplet system around 1400 MeV. The PDG listing suggests a mixing between the states at 1270 and 1400 but an interesting alternative is to think of the 1270 state as a hadro-molecular system, that is, a four-quark, L=0, isodoublet system with equivalent descriptions:

$$(\bar{s}u\ d\bar{d}) \quad \Leftrightarrow \quad K^0\rho^+ \quad \text{or} \quad K^+(\omega^0+\rho^0)/\sqrt{2} \qquad (1)$$

$$(\bar{s}d\ u\bar{u}) \quad \Leftrightarrow \quad K^+\rho^- \quad \text{or} \quad K^0(\omega^0-\rho^0)/\sqrt{2} \qquad (2)$$

The appearance of $K\rho$ and $K\omega$ modes is very natural in this picture: within the hadro-molecular system the bound ρ (or ω) decays leading to the observed final states.

The concept of non-standard meson and baryon states is not new—a multi-quark explanation has been proposed for the $f_0(975)$ and $a_0(980)$[4], for example. The study of heavy resonances which appear to exist at the boundary between QCD and nuclear physics may shed some light on the nature of the confinement process.

Within the quark model the ground state neutral B mesons consist of a $\bar{b}d$ (B^0) or a $\bar{b}s$ (B^0_s). To date only one excited state, the B^*, has been observed. The mass of this 1^- (quark model assignment) state is 5324.6±2.1 MeV. As this state is relatively narrow and much less than a pion mass above the B meson ground states, decays to the ground state take place radiatively. Unfortunately the signature photon energy is too low for presently configured collider spectrometers.

Figure 2 outlines the relationship between the ground states and first excited P-wave states for the K, D, and B systems. The horizontal bars about the central mass values are not uncertainties but rather represent single line widths (±1Γ). None of the excited beauty meson P-waves have yet been seen; the prediction that they lie some 450 MeV above the S-wave states reflects the first order domination of the mass of the light quarks in the splittings (which go as the reciprocal of the reduced mass). At the 1993 Snowmass conference the results[5] of more detailed calculations for masses of the 1^3P_1 and 1^3P_2 excited D_s, B, and B_s mesons were presented. Figure 2 also shows the $K_1(1270)$ state, discussed above, and where analogs of this hadro-molecular-interpreted state would lie in the charm and beauty systems.

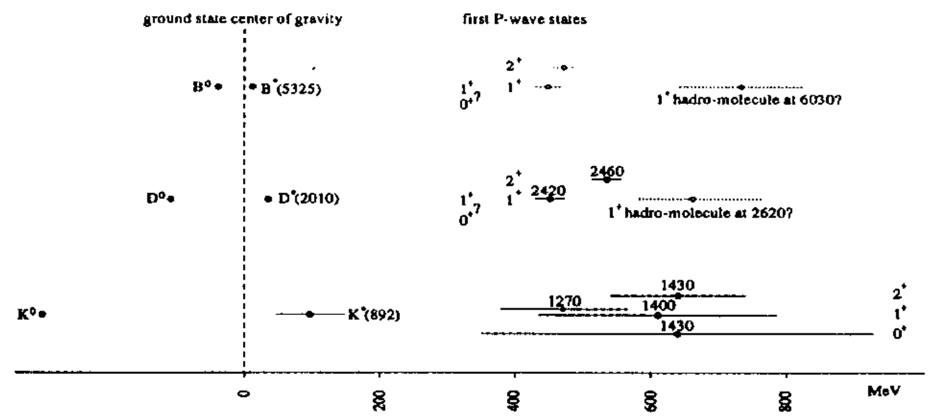

Figure 2. S-wave and P-wave Heavy Flavor States

Whether or not there is a significant cross section for these excited states, relative to the ground states, is an open question. Presumably a high statistics charm hadro-production experiment such as FNAL E-791 could address the question of resonance production in the D sector. Results from e^+e^- machines and photoproduction experiments may not necessarily be indicative of hadro-production trends.

Excited beauty mesons will tumble down to the lowest lying ground states (either B or B_s) through a combination of radiative transitions and strong decays. As such they will appear to come from the primary interaction vertex. Due to parity conservation the 1^3P_1 state cannot decay directly by pion emission to the B ground state but can go through the B^*. Single pion emission of the 1^3P_2 (and presumably broader 1^3P_0) is allowed. One variant of self-tagging would involve identifying a charged pion whose direction vector is close to the neutral B vector and whose $\pi^{\pm}B^0$ invariant mass is close to the 1^3P_2. We note however a couple reasons why this type of resonance self-tagging may be difficult:

1. Although the production of P-wave states may be large, only a restricted number of decays—those with a charged pion and neutral B meson in the final state—are relevant. For example, given equal initial populations of the 1^3P_2 (B^{**+},B^{**0},$\bar{B}^{**0}$, B^{**-}), only one-third of the strong decays will lead to the desired final state.

2. Contributions from dipion decays such as $B^{**0}\rightarrow\pi^+\pi^-B^0$ where one of the pions is soft and missed and the other appears to resonate with the B^0 with consequent flavor dilution. A hadro-molecular state (BV, V=ρ,ω) would fall in this category.

It would appear that flavor self-tagging will not work for B_s^0 since the $\bar{b}s$ system has zero isospin and consequently no transitions involving single charged pions. If any or all of the P-wave states lie below the m_B+m_K threshold, those states will decay by E1 γ emission. Above this threshold B_s^0 excited states will fall apart into B+K (or B+Kπ) and consequently short circuit the B_s^0. This is directly analogous to the more familiar situation in charmonium where transitions to low lying states are effectively quenched above the open charm thresholds, $2m_D$ and $m_D+m_{D^*}$.

We conclude by observing that there is a rich field of spectroscopy to be mined. Not only is it interesting in its own right, but it can clarify outstanding issues in light quark spectroscopy as well as serve as a technical basis for symmetry studies such as CP violation.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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5. From a working session talk (*Properties of Excited B Mesons*) presented by C. Quigg at the Snowmass 1993 B-Physics Workshop. These results will soon exist in pre-print form: E. Eichten, C. Hill, and C. Quigg, FERMILAB—Pub-93/255—T.