

Heavy Quark Spectroscopy

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With the discovery of new states in recent years, interest in spectroscopy has revived. Recent experimental results in heavy flavour spectroscopy are reviewed, including charmonium, bottomonium, charmed mesons and baryons and bottom mesons.

1. INTRODUCTION

Classical mesons are bound states of a quark and an anti-quark. However, very similar properties can be expected from states with more constituents, like glueballs, hybrids with quark, anti-quark and (valence) gluon or states with two quarks and two anti-quarks.

In mesons with open or hidden heavy flavour, one $q\bar{q}$ pair must be present, therefore exotic mesons can only be hybrids $q\bar{q}g$, meson molecules $q\bar{q}q\bar{q}$, diquark bound states $qq\bar{q}\bar{q}$ or states with even more constituents.

Within the recent past, new mesons with heavy quarks have been observed, and several known ones have been confirmed or measured with improved precision. Especially in the charmonium sector the number of new mesons found exceeds the number of available states in the $c\bar{c}$ spectrum.

The quantum numbers of new mesons can be measured in some reactions. Production in e^+e^- annihilation either directly or after one electron has radiated off a photon (initial state radiation) have the quantum numbers of a photon, $J^{PC} = 1^{--}$. Photon photon fusion leads to final states with even C -parity and in general J^{++} ($J \neq 1$), *even* $^{-+}$. The quantum numbers of states produced in two-body B meson decays can be obtained in a partial wave analysis of production and decay angles.

2. BOTTOMONIUM SPECTROSCOPY

The known bottomonium spectrum is shown in Fig. 1.

The vector bottomonium states were the first hadrons with b quarks discovered [1]. Their widths were always subject to large systematic uncertainties. Recent analyses by the CLEO collaboration [2] of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ have improved our knowledge substantially on the essential properties, $\Gamma(\Upsilon \rightarrow e^+e^-)$ and $\mathcal{B}(\Upsilon \rightarrow \mu^+\mu^-)$, leading to new and more precise values of their total widths Γ_{tot} . A measurement by BABAR [3] has taken into account the subtleties of a $4S$ wave function and lead to new values of $\Gamma(\Upsilon \rightarrow e^+e^-)$ and Γ_{tot} of the $\Upsilon(4S)$.

Hadronic transitions via emission of a pion pair have now also been observed from the $\Upsilon(4S)$ to the $\Upsilon(1S)$ and $\Upsilon(2S)$ [4]. The new transitions—added to other

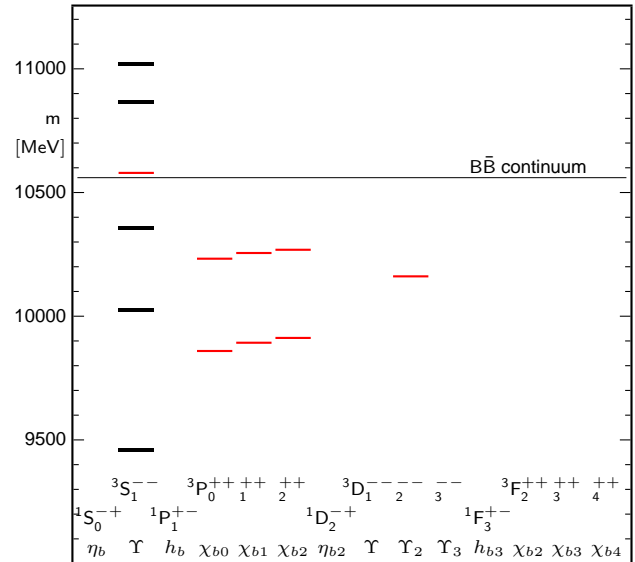


Figure 1: The spectrum of known bottomonium states. Data for those in red have been updated recently.

hadronic transitions observed previously—reveal a peculiar pattern: While most transitions have a $\pi\pi$ mass spectrum peaking at the high end, those with $\Delta n = 2$ as $3S \rightarrow 1S$ and $4S \rightarrow 2S$ show a double peak at low and high masses. No explanation for this effect is known to me.

The $\Upsilon(1D)$ state has already been observed by CLEO two years ago [5], while other states with $L > 1$ are still missing.

3. CHARMONIUM SPECTROSCOPY

The charmonium spectrum below open charm threshold has been completed through the confirmation of the h_c state by two experiments [6].

3.1. The X, Y, Z States

Many new observations in the charmonium sector have been made recently. The oldest is $X(3872)$ observed in $X(3872) \rightarrow \pi^+\pi^- J/\psi$ [7, 8], a narrow state ($\Gamma < 2.3\text{MeV}$) with mass $(3871.2 \pm 0.4)\text{MeV}$. It is produced in hadronic B meson decays. The decay

rate $X(3872) \rightarrow \gamma J/\psi$ is lower by a factor 0.19 ± 0.07 [9], and establishes even C-parity. It has not been seen in $\gamma\gamma$ fusion and e^+e^- annihilation [10]. The $\pi\pi$ mass spectrum peaks at the high end, consistent with ρ^0 dominance. This and a full angular analysis of $X(3872) \rightarrow \pi^+\pi^- J/\psi$ [11] rule out all assignments except $J^{PC} = 1^{++}$. That would be χ_{c1} , but there is no vacant slot in the $c\bar{c}$ spectrum for such a state.

As an exotic state, its isospin might be different from 0. In fact, the transition $\chi_{c1}(nS) \rightarrow \pi^+\pi^- J/\psi$ is violating isospin conservation, and can therefore be no strong transition. However, no charged partner is observed in B decays [12]. On the other hand, there is some indication of the isospin-allowed $X(3872) \rightarrow \omega J/\psi$ [13], although kinematics allows only $\pi^+\pi^-\pi^0$ below the central value of the ω mass.

An inclusive search in B decays to determine the absolute branching fractions of the $X(3872)$ was not (yet) successful [14].

A peak at threshold in $D^0\bar{D}^0\pi^0$ at 3875MeV [15] is probably the same $X(3872)$ state.

Since it does not fit into the $c\bar{c}$ spectrum, the $X(3872)$ is an exotic meson with $J^{PC} = 1^{++}$ and most likely $I = 0$.

Another new state has been observed in $e^+e^- \rightarrow c\bar{c}c\bar{c}$ -production: $e^+e^- \rightarrow J/\psi X(3940)$, $X(3940) \rightarrow D^*D$ [16]. It is probably narrow with a measured $\Gamma = (39 \pm 26)\text{MeV}$, and is not seen in the $\bar{D}D$ final state.

A second state at the same mass has been observed in B decays, which seems to be broader with $\Gamma = (87 \pm 33)\text{MeV}$ and decays into $\omega J/\psi$ [17]. It is not seen in either $\bar{D}D$ or \bar{D}^*D . All these properties distinguish it from the $X(3940)$, so it has been called $Y(3940)$.

A third state at the same or a little bit smaller mass has been called $Z(3930)$. It is produced in $\gamma\gamma$ fusion and decays to $\bar{D}D$ [18]. The helicity angle distribution favors spin 2, so it is likely a 2^{++} meson. Its mass would fit the expected $c\bar{c}$ -meson $\chi_{c2}(2P)$ so it is the least peculiar of the new mesons.

At a somewhat higher mass, another state was observed in radiative e^+e^- annihilation $e^+e^- \rightarrow \gamma Y(4260)$ decaying into $\pi^+\pi^i J/\psi$ [19]. A scan by CLEO-c [20] reveals an enhancement at direct production from e^+e^- annihilation at this energy, with a ratio $\pi^+\pi^- J/\psi$ to $\pi^0\pi^0 J/\psi$ of approximately 2 : 1 as expected for a $I = 0$ hadronic transition between vector charmonium states. However, vector charmonium states are expected to show up in the inclusive hadronic cross section of e^+e^- annihilation (in Fig. 40.7 in the PDG book [22]), but at $\sqrt{s} = 4260\text{MeV}$ there is a dip!

The state has been possibly observed at the 3σ level in hadronic B decays [8]. The decay to $\bar{D}D$ is not observed and is less than 7.6% of $\pi^+\pi^- J/\psi$ at 95% CL [21].

There is also a state at mass 4320MeV decaying into $\pi^+\pi^-\psi(2S)$ [23].

In summary, several new states have been observed recently that do not match with available slots in the $c\bar{c}$ spectrum. At least 4 of these states have to be considered exotic mesons.

As of their true nature, there exist many speculations [24], but no conclusive arguments have been found for a unique solution for any of these.

4. OPEN FLAVOUR MESONS

In contrast to quarkonia, the spectrum of heavy mesons with open flavour is given by eigenstates to L and j_q , the total angular momentum (orbital L plus spin S_q) of the light quark, rather than L and S , the sum S_q plus S_Q of both quark spins. The corresponding notation ${}^{(j)}L_J^P$ is used in figure 2.

4.1. B , B_s and B_c Mesons

There are recent measurements of excited B mesons $B_J^0 \rightarrow B^{(*)+}\pi^-$ [25, 26]. Unfortunately, the masses reported by CDF and D0 differ significantly, and more data are needed to get at precise masses and widths.

D0 has also observed evidence for the B_{s2}^* meson at a mass of $(5839.1 \pm 1.4 \pm 1.5)\text{MeV}$ [27]. This value has been confirmed after this conference by CDF with higher precision [28].

It is also worthwhile to mention that a clear peak of 39 fully reconstructed events of the double-heavy B_c meson has been presented this year [29].

4.2. D_s Mesons

A strong decay of excited D_s mesons has to conserve isospin and thus goes to $D^{(*)}K$ final states. The spectrum in figure 2 shows the expected states and the $D^{(*)}K$ thresholds.

Recently observed new states $D_{s0}^*(2317)$ and $D_{s1}^*(2460)$ [32] are both below the threshold of their allowed decay mode, and have been observed decaying into $D_s^+\pi^0$ and $D_s^{*+}\pi^0$, respectively. Consistently, these states are narrow with upper limits of a few MeV for their widths.

Their spin-parity assignments are consistent with their observation (or non-observation) in the transitions to $D_s\pi^0$, $D_s\gamma$, $D_s^*\pi^0$, and $D_s\pi^+\pi^-$ [33], and with their decay angular distributions [34]. What is puzzling about these mesons is that all model calculations (unless heavily tweaked) predict significantly larger masses for these states in the $c\bar{s}$ system which makes them also good candidates for exotic mesons.

Another state $D_{sJ}(2860)$ has been observed recently by BABAR [35] which decays into DK . Although it has been suggested to be a radial excitation of the exotic $D_{s0}^*(2317)$ meson, it could also be an ordinary $c\bar{s}$ meson.

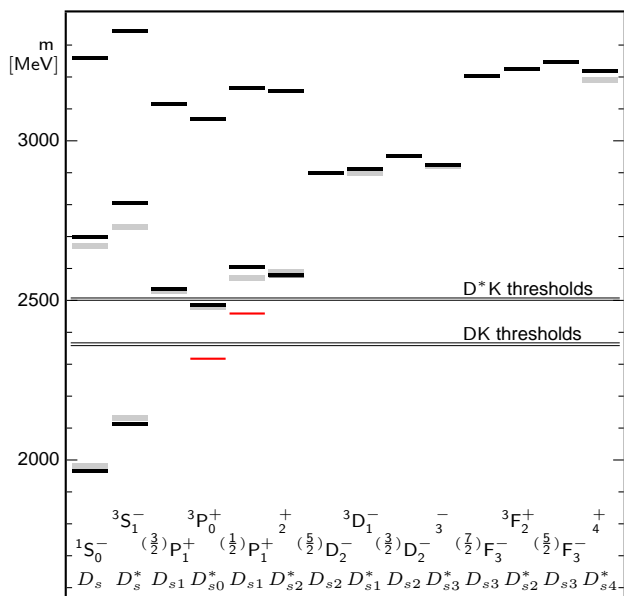


Figure 2: The spectrum of $c\bar{s}$ states. Theoretical predictions are from [30] (grey) and [31] (black). The puzzling new states are the thin lines in red.

5. CHARMED BARYONS

Several new excited baryons have been added to the list of known hadrons recently. They fill up the existing open slots in the spectrum of heavy baryons.

In the cud system, the $\Lambda_c^+(2880)$ [36] and a new state $\Lambda_c^+(2940)$ have been observed to decay into $D^0 p$ [37]. Their assignment $I = 0$ is supported by the absence of a partner with the $D^+ p$ final state.

There is a triplet of $I = 1$ mesons $\Sigma_c^+(2800)$ decaying to $\Lambda_c^+ \pi$ [38].

New cus baryons $\Xi_c^+(2980)$ and $\Xi_c^+(3077)$ decaying to $\Lambda_c^+ K^- \pi^+$ [39] have also been seen, and there is evidence for their isodoublet partners $\Xi_c^0(2980)$ and $\Xi_c^0(3077)$ decaying to $\Lambda_c^+ K_S^0 \pi^+$ [40].

6. SUMMARY

The appearance of states in excess to the $c\bar{c}$ spectrum indicates clearly the presence of exotic mesons which are made of more constituents than just a quark and an anti-quark. The interpretation of the new states is a challenge to non-perturbative QCD calculations, which will hopefully be able to calculate the spectrum of ordinary and exotic mesons, and thus be able to predict the masses and widths of by now undiscovered states.

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