Heavy Flavour Spectroscopy

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Study of heavy hadrons is a valuable test of QCD predictions and a search for exotic phenomena. In this review the recent experimental results on hadrons of heavy flavours are presented. These include measurements of properties of the known $c\bar{c}$ and $b\bar{b}$ quarkonium states, as well as observations of new hadrons, like charmed-strange mesons, beauty baryons and a ground bottomonium state, the η_b. Also charmonium-like XYZ resonances, being candidates for exotic particles, are reviewed.

1 Introduction and motivation

Study of heavy hadrons is a study of strong interactions and a test of QCD predictions. Forces binding quarks into hadrons of either meson or baryon configuration are described by QCD. Quarks are considered to be bound into hadrons by single-gluon exchange plus a linear confining potential. The potential models, incorporating the general features of QCD, describe the spectra and properties of the hadrons. This allows one to obtain a picture of hadron multiplets including masses of resonances, their electromagnetic and hadronic transitions, decays, fine and hyperfine splittings between the states, etc. Since the models give detailed predictions for such observables, they can be validated by comparing with experimental measurements. Measured variances from theoretical predictions could indicate new phenomena. Alternative way to generate QCD observables are numerical lattice QCD computations which also can be tested by experiments.

The QCD-motivated models predict also an existence of hadrons of more complex structure than conventional mesons or baryons, such as hybrids and multiquark states of either molecular or tetraquark configuration. Molecular state [1] consists of two mesons weakly bound through pion exchange. Because of a loose binding, the comprising mesons decay as if they are free. Tetraquark is a tightly bound four-quark state of for example diquark-diantiquark configuration where the comprising quarks group into colour-triplet clusters interacting by a gluon exchange [2]. In decay process the quarks rearrange to form colour-singlet mesons which subsequently dissociate. Some multiquarks can be easily distinguished from conventional states, for example ones with non-zero charge $[cd\bar{c}\bar{u}]$ or strangeness $[cd\bar{c}\bar{s}]$. Hybrid mesons in addition to quark-antiquark component contain an excited gluon [3]. The lowest charmonium hybrids are predicted by lattice QCD to have masses of about $4.2\mathrm{GeV}/c^2$. Some of the hybrids can have exotic quantum numbers like $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$, not possible for conventional states. Observation of state with such a spin-parity would indicate existence of exotic resonance.

Model calculations for heavy hadrons are easier and more reliable than for light ones. Also spectra of heavy hadrons are much cleaner with regard to dense spectrum of light states. Therefore exotic states containing for example $c\bar{c}$ or $b\bar{b}$ are expected to be identified easier than the ones predicted in the light spectrum. However no unambiguous evidence for exotic states has been found till recently when the XYZ particles were observed giving a hint of the exotic spectroscopy. All these make spectroscopy of heavy hadrons even more interesting.

2 Charmed-strange mesons

Charmed-strange mesons are heavy-light systems for which the potential models employ the heavy quark symmetry [4]; in this picture such mesons become similar to the hydrogen atom.

In the spectrum of $c\bar{s}$ multiplets there are two S-wave states, D_s^+ and D_s^{*+} with $J^{PC} = 0^-, 1^-$, whereas orbitally excited P-wave states are due to relativistic corrections split into four states with quantum numbers of 0^+, 1^+, 1^+, 2^+, and are respectively identified with $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$, $D_{s1}(2536)^+$ and $D_{s2}^*(2573)^+$. As properties of the states with masses at 2317 MeV/c^2 and 2460 MeV/c^2 contradict predictions of the most potential models, more exotic assignments have been also proposed for the new states, like DK molecules, multiquark states or mixtures of P-wave $c\bar{s}$ meson with $c\bar{s}q\bar{q}$ tetraquark; chiral partners of D_s and $D_s^\star$ [5]. Although some quark models already succeeded in reproducing the low masses of these states by considering both chiral and heavy quark symmetries [6], it is clear that our understanding of $c\bar{s}$ spectroscopy is incomplete.

Two more $c\bar{s}$ mesons, the $D_{s1}^*(2700)^+$ 1^- state [7] and the $D_{sJ}^*(2860)^+$ [8], observed in their decays into the DK final states, are candidates for either radial or higher orbital excitations. Additional measurements of their properties, especially of new decay modes, may help to distinguish between these two interpretations.

Recently BaBar has studied the mass spectrum of $D^{(*)}K$ inclusively produced in e^+e^- annihilation [9]. In the DK system the $D_{s1}^*(2700)^+$ and $D*_{sJ}$ $(2860)^+$ states, are confirmed, whereas in the D^*K mass distribution, in addition to these two mesons also a new broad state has been found with mass of 3040 MeV/c^2 and width of about 240 MeV/c^2. Nonobservation of the $D_{sJ}(3040)^+ \to DK$ suggests unnatural parity (0^-, 1^+, 2^-, etc.) for this meson, whereas observation of the $D_{s1}^*(2700)^+$ and $D_{sJ}^*(2860)^+$ in both DK and D^*K final states rules out 0^+ assignment and implies natural parities (1^-, 2^+, 3^-) for them. Ratios of branching fractions have been measured to be: $\frac{\mathcal{B}\left(D_{s1}^*(2700)^+ \to D^*K\right)}{\mathcal{B}\left(D_{s1}^*(2700)^+ \to DK\right)} = 0.91 \pm 0.13 \pm 0.12$ and $\frac{\mathcal{B}\left(D_{sJ}^*(2860)^+ \to D^*K\right)}{\mathcal{B}\left(D_{sJ}^*(2860)^+ \to DK\right)} = 1.10 \pm 0.15 \pm 0.19$. This favours for the $D_{s1}^*(2700)^+$ an interpretation as first radial excitation of D_s^{*+}, the 2^3S_1 [10]. For the $D_{sJ}^*(2860)^+$ and the $D_{sJ}(3040)^+$ interpretations as radial excitations with respectively $J^P = 3^-$ and $J^P = 1^+$ are proposed [11].

3 Charmonia

All the $c\bar{c}$ states predicted to have masses below the threshold for open charm production have been observed. Discovery of the $\eta_c(2S)$ as well as of the most elusive state h_c, have completed the list of low lying charmonia. All these states have properties that agree quite well with the predictions of the potential models. As for the states above the $D\bar{D}$ mass threshold, despite recent experimental progress, situation is not well established and many resonances remain unobserved. The known charmonia above the $D\bar{D}$ mass threshold: $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ are 1^{--} states corresponding respectively to 1^3D_1, 3^3S_1, 4^3S_1 and 2^3D_1. Their parameters have been determined from the fit to the R_c spectrum defined as a ratio of the measured inclusive hadronic cross-section $e^+e^- \to c\bar{c}$ to the calculated cross-section for

$e^+e^- \to \mu^+\mu^-$. The R_c values measured by BES in energy scans at center-of-mass (cms) energies between 3.7 and 5.0 GeV have been recently refitted with interferences between the ψ states allowed [12]. As a result, some of the resonance parameters, especially of the $\psi(4160)$, have significantly changed with respect to the previous, incoherent approach [13]. However fitting such inclusive data is complicated and yields the resonant parameters being strongly model-dependent as there are many decay channels allowed, like $D^{(*)}\bar{D}^{(*)}$ and $D_s^{(*)}\bar{D}_s^{(*)}$. To reduce this effect, one could fit exclusive cross-sections for $e^+e^- \to D^{(*)}\bar{D}^{(*)}$ accessed through initial state radiation (ISR) process, once they are measured with statistics high enough.

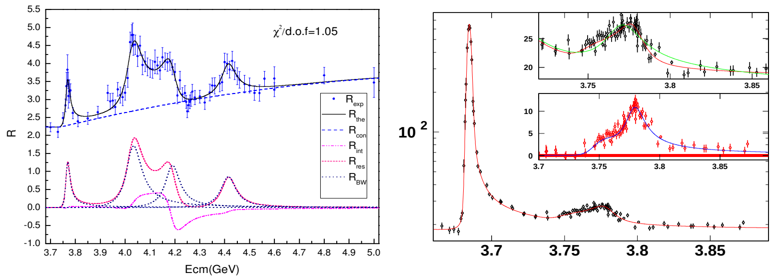

Figure 1: (Left) Fit to the R_c values. The solid curve shows the best fit, R_{BW} shows contributions from each resonance, R_{int} shows interference. (Right) Inclusive hadronic cross-section (in $[nb]$) versus the cms energies. In the upper sub-figure the fit for the one amplitude hypothesis (green line) is compared with the fit for hypothesis with two resonances (red line).

BES has also examined fine-grained R_c spectrum in the cms energy region between 3.70 and 3.87 GeV. While the $\psi(3770)$ resonance was believed to be the only structure in that region, BES found a line-shape of the $\psi(3770)$ to be anomalous [14]. The data significantly favour a fit with the two resonance hypothesis over the fit with a single $\psi(3770)$ resonance (Fig. 1). This new resonance structure, unless these are some dynamics effects distorting the pure Breit-Wigner line-shape (for example rescattering of $D\bar{D}$), may help to solve the puzzle related to non-$D\bar{D}$ decays of the $\psi(3770)$. Large inclusive non-$D\bar{D}$ branching fraction (15%), has not been confirmed by searches for exclusive decays; the summed non-$D\bar{D}$ decays are less than 2%.

Unobserved ground charmonia $1^3D_{c2,c3}$ and 1^1D_{c2} are predicted to have masses close to the $\psi(3770)$ mass, relatively small widths and are expected to decay to lower-lying charmonia. Therefore their observation is feasible. The next unseen multiplet are radially excited states $\chi_{c1,c2,c3}(2P)$ $(2^3P_{c1,c2,c3})$ and $h_c(2P)$ (2^1P_{c1}). They should lie in mass range of $3800-3980$ MeV$/c^2$ and have widths of $30-150$ MeV$/c^2$. The $Z(3930)$ observed in its decay to the $D\bar{D}$ and bearing quantum numbers of 2^{++}, is identified with the $\chi_{c2}(2P)$ [15]. Some of the other recently found charmonium-like states, the XYZ, could be candidates for the missing charmonia. However their properties are either unusual or forbidden for conventional $c\bar{c}$ states and, as such, are candidates for the exotic hadrons, although most of them still await confirmation and need their properties to be further studied before any decisive interpretation is made.

4 Charmonium-like states

4.1 $X(3872)$

Out of the XYZ states, the first and most famous one is the $X(3872)$ observed by Belle in the $M(J/\psi\pi^+\pi^-)$ spectrum in $B^+ \to J/\psi\pi^+\pi^-K^+$ decays and further confirmed by CDF and D∅ to be produced in $p\bar{p}$ collisions, as well as by BaBar [16]. Mass of the $X(3872)$ has been recently precisely measured by CDF to be $m_{X(3872)} = 3871.61 \pm 0.16 \pm 0.19$ MeV$/c^2$ (Fig. 2) [17], its total width is $\Gamma_{X(3872)} < 2.3$ MeV$/c^2$. The $X(3872)$ mass is in close vicinity of the sum of the D^0 and D^{*0} masses (3871.81 ± 0.36 MeV$/c^2$). Whether the $X(3872)$ lies below or above that threshold still remains a question important to understand a nature of the $X(3872)$.

In addition to $J/\psi\pi^+\pi^-$ where dipion mass is consistent with originating from $\rho(770)$ [18], also evidence of the $X(3872) \to J/\psi\pi^+\pi^-\pi^0$ mode was found [19]; comparable rates of these decays suggest large isospin violation. An evidence of radiative decays to $J/\psi\gamma$ and $\psi(2S)\gamma$ [20] indicate C-parity$= +$ for the $X(3872)$. The mentioned properties along with results of the CDF angular analysis [21] strongly favour $J^{PC} = 1^{++}$.

Narrow near-threshold enhancement which could originate from the $X(3872)$, has been observed in the mass distribution of the $D^0\bar{D}^{*0}$ system produced in $B \to KD^0\bar{D}^{*0}$ decays (Fig. 2) [22]. New Belle measurement gives a position of the peak to be $3872.6^{+0.5}_{-0.4} \pm 0.4$ MeV$/c^2$, thus is in good agreement with the $X(3872) \to J/\psi\pi^+\pi^-$ mass; the mass measured by BaBar, $3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV$/c^2$, is slightly larger.

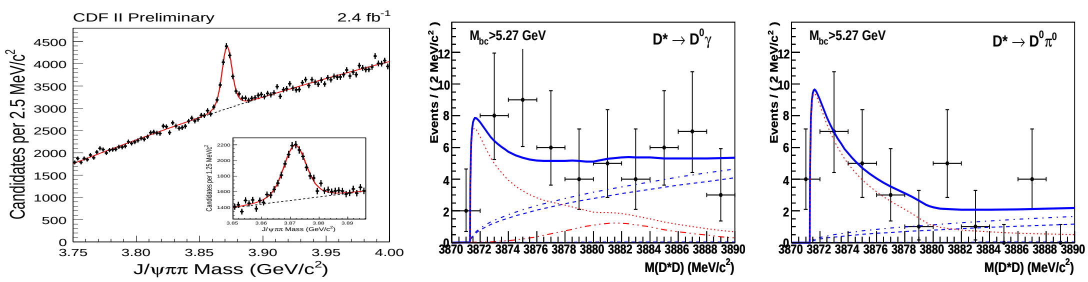

Figure 2: Left: $M(J/\psi\pi^+\pi^-)$ distribution from CDF. Middle and right: $M(D^0\bar{D}^{*0})$ distributions for $D^{*0} \to D^0\gamma$ and $D^{*0} \to D^0\pi^0$ from Belle. Red-dotted line is fit result with the Flatté parameterization, blue-solid line is fit using the Breit-Wigner function.

As finding 1^{++} charmonium fitting the $X(3872)$ failed, many theorists suggested that this particle may be a four-quark meson. A mass of the $X(3872)$ has triggered speculations that it is a molecular bound state of D^0 and $\bar{D}^{*0}$ lying just below the D^0D^{*0} threshold [23]. Large branching fraction of $X(3872) \to D^0\bar{D}^{*0}$, measured to be one order of magnitude larger than for $X(3872) \to J/\psi\pi^+\pi^-$, supports this interpretation. However the large partial width of $X(3872) \to \psi(2S)\gamma$ with respect to $J/\psi\gamma$ is problematic for the molecular scenarios, whereas can be naturally explained in the framework of quark models. To overcome this, an admixture of $c\bar{c}$ component in the $X(3872)$, in addition to the molecular components, was proposed [24]. Such a charmonium admixture could also explain a large cross-section for prompt production of the $X(3872) \to J/\psi\pi\pi$ seen by CDF and D∅ [25]; formation of J/ψ from largely separated D^0 and $\bar{D}^{*0}$ constituents is far more difficult than from $c\bar{c}$ component.

Another four-quark interpretation suggests that the $X(3872)$ is a tightly bound diquark-diantiquark system [26]. In this scenario one expects a doublet, $X_u = [cu][\bar{c}\bar{u}]$ and $X_d = [cd][\bar{c}\bar{d}]$, produced respectively in charged $B^+ \to K^+ X_u$ and neutral $B^0 \to K^0 X_d$ decays and having masses which differ by a few MeV [28]. However studies by Babar and Belle have not revealed such a mass split [27]; CDF have found no evidence of two states either. In addition, an isospin partner state with quark composition $[cu][\bar{c}\bar{d}]$ is expected to exist and decay to the $J/\psi\pi^+\pi^0$. Nevertheless any charged partner of the $X(3872)$ has not been observed so far [29].

Thus, in view of the mentioned experimental results, interpretation of the $X(3872)$ as a mixture of the molecule with the conventional $c\bar{c}$ state seems to be favourable.

4.2 News on Y family

Another states which await understanding are $Y(4008)$, $Y(4260)$, $Y(4360)$ and $Y(4660)$. These are 1^{--} resonances observed in the $J/\psi\pi^+\pi^-$ and $\psi(2S)\pi^+\pi^-$ systems produced in the ISR reaction $e^+e^- \to \gamma_{ISR} Y$ [30]. Their parameters do not coincide with any of the vector charmonia observed so far and are inconsistent with the quark model calculations for charmonia. Although the masses of the Y states are above the threshold for decays to final states like $D\bar{D}$, $D\bar{D}^*$ or $D^*\bar{D}^*$, there are no clear peaks in the cross-sections for $e^+e^- \to D^{(*)}\bar{D}^{(*)}$ [31] that could originate from the Y states.

Recently BaBar has fitted invariant mass spectra of the $D^{(*)}\bar{D}^{(*)}$ systems produced in the ISR process. In addition to the ψ vector states, a contribution from the $Y(4260)$ resonance has been coherently added. No evidence of the $Y(4260)$ has been found; the corresponding upper limits are $\frac{\mathcal{B}(Y(4260)\to D\bar{D})}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 1$, $\frac{\mathcal{B}(Y(4260)\to D\bar{D}^*)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 34$, $\frac{\mathcal{B}(Y(4260)\to D^*\bar{D}^*)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 40$ [32]. Instead, the partial decay widths for the hadronic transitions of the Y states to $J/\psi\pi\pi$ or $\psi(2S)\pi\pi$ are very large ($\mathcal{O}$(MeV)) and, as such, unlikely for the conventional $c\bar{c}$ states. Other possible interpretations of the Y states are: charmonium hybrids predicted in this mass region and expected to decay dominantly into $D\bar{D}_1$; $cq\bar{c}\bar{q}$ tetraquarks, $D^*\bar{D}^*$, $D\bar{D}_1$ and $D^*\bar{D}_0^*$ molecules or just S-wave charm meson thresholds [33]. More experimental information on the decay properties is needed to test these scenarios, such as searching for other close charm decay modes ($J/\psi\pi^0\pi^0$, $J/\psi\eta$, $\chi_c\omega$), as well as open charm channels, especially $D\bar{D}_1$ followed by $\bar{D}_1 \to \bar{D}^*\pi$. In a Belle search for the latter decay channel, amplitudes of the Y states obtained in the fit to the $M(D^0D^{*-}\pi^+)$ spectrum are found to be consistent with zero. Upper limit $\frac{\mathcal{B}(Y(4260)\to D^0D^{*-}\pi^+)}{\mathcal{B}(Y(4260)\to J/\psi\pi^+\pi^-)} < 9$ [34], although not stringent with currently available statistic, does not support the hybrid interpretation.

4.3 Y(4140)

An evidence of the $Y(4140)$ has been found nearby mass threshold of the $J/\psi\phi$ system produced in the $B^+ \to J/\psi\phi K^+$ decays exclusively reconstructed by CDF [35]. Mass and width of the structure (Fig. 3) have been measured to be $4143.0\pm2.9\pm1.2\,\mathrm{MeV}/c^2$ and $11.7^{+8.3}_{-5.0}\pm3.7\,\mathrm{MeV}/c^2$; the $Y(4140)$ signal yield 14 ± 5 has significance of 3.8σ. The $Y(4140)$ could be a candidate for a multiquark state of $[cs\bar{c}\bar{s}]$ composition, for example a $D_s^{*+}D_s^{*-}$ molecule [36].

Belle having four times larger sample of the $B^+ \to J/\psi\phi K^+$ decays reconstructed, have found a yield of the $Y(4140)$ to be only $7.5^{+4.9}_{-4.4}$ from the fit with the resonance parameters fixed to the CDF ones (Fig. 3) [37]. Because of low reconstruction efficiency close to the $M(J/\psi\phi)$ threshold, Belle data have sensitivity lower than the CDF one. The upper limit set by Belle

$\mathcal{B}(B^+ \to Y(4140)K^+) \times \mathcal{B}(Y \to J/\psi\phi) < 6 \times 10^{-6}$ remains in agreement with this branching fraction product measured by CDF to be $(9.0 \pm 3.4 \pm 2.9) \times 10^{-6}$.

Also Belle has investigated the $J/\psi\phi$ system produced in the $\gamma\gamma$ fusion processes [38]. Such a reaction allows states with $J^{PC} = 0^{++}$ and 2^{++} to be formed. No signal has been found in $M(J/\psi\phi)$ around 4.14 GeV/c^2; a narrow enhancement around 4.35 GeV/c^2 is seen instead (Fig. 3). Upper limit on the product of the two-photon decay width of the $Y(4140)$ and its branching fraction, $\Gamma_{\gamma\gamma}(Y(4140))\mathcal{B}(Y(4140) \to J/\psi\phi) < 41$ eV for $J^P = 0^+$ or < 6.0 eV for $J^P = 2^+$, are much lower than predicted for the $Y(4140)$ if it was the $D_s^{*+}D_s^{*-}$ molecule.

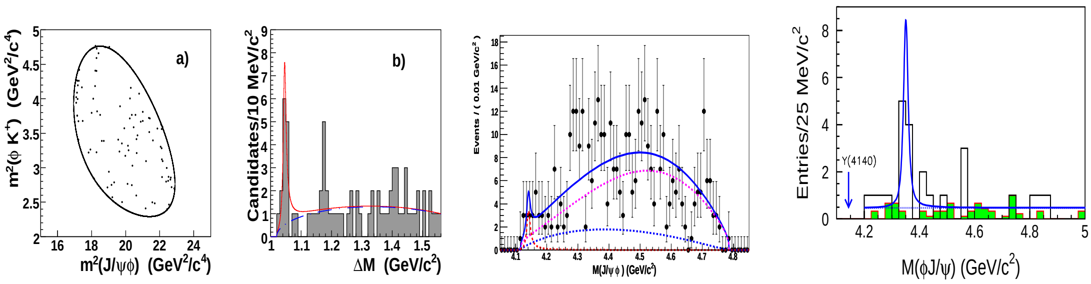

Figure 3: Left: Dalitz plot of $B \to J/\psi\phi K$ decays and $M(J/\psi\phi) - M(J/\psi)$ distribution from CDF. Middle: $M(J/\psi\phi)$ from B decays in Belle. Right: $M(J/\psi\phi)$ produced in $\gamma\gamma$ in Belle.

4.4 Y(3940)

The $Y(3940) \to J/\psi\omega$ in $B \to KJ/\psi\omega$ decays was observed by Belle and confirmed by BaBar [39], although its mass and total width measured by Belle ($m_{Y(3940)} = 3943 \pm 11 \pm 13$ MeV/c^2, $\Gamma_{Y(3940)} = 87 \pm 22 \pm 26$ MeV/c^2) and BaBar ($m_{Y(3940)} = 3914.6^{+3.8}_{-3.4} \pm 2$ MeV/c^2, $\Gamma_{Y(3940)} = 34^{+12}_{-8} \pm 5$ MeV/c^2) slightly differ. Large production rate in B decays ($\mathcal{O}(10^{-5})$) implies $\Gamma(Y(3940) \to J/\psi\omega) > 1$ MeV, thus larger than for any $c\bar{c}$ state above open charm threshold. However the $\chi_{c1}(2P)(\equiv Z(3930))$ charmonium assignment cannot be excluded.

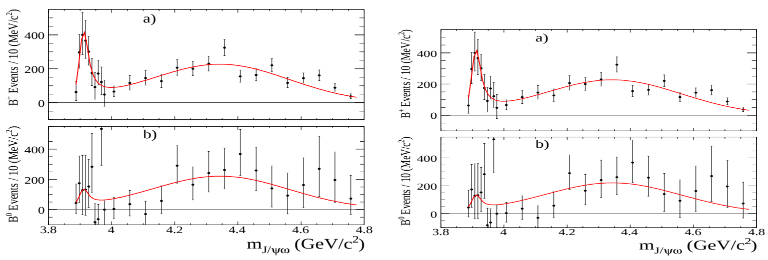

Figure 4: Left: $M(J/\psi\omega)$ distributions for charged (top) and neutral (bottom) $B \to KJ/\psi\omega$ decays from BaBar. Right: $M(J/\psi\omega)$ distributions from two-photon production in Belle.

In the recent study of the $J/\psi\omega$ produced in the $\gamma\gamma$ process, Belle have observed a significant peak in the $M(J/\psi\omega)$ distribution [40]. Its parameters, $m = 3915 \pm 3 \pm 2$ MeV/c^2 and $\Gamma = 17 \pm 10 \pm 13$ MeV/c^2, are consistent with the $Y(3940)$ (Fig. 4). Product of the two-photon decay width and $J/\psi\omega$ partial width are $61 \pm 17 \pm 8$ eV for 0^+ and $18 \pm 5 \pm 2$ eV for 2^+ case. The 0^+ and 2^+ spin-parity assignments cannot be distinguished with the current data sample. Assuming two-photon width typical for an excited charmonia $\Gamma_{\gamma\gamma} \sim \mathcal{O}(1 \text{ keV})$ implies a partial width of $\Gamma(Y(3940) \to J/\psi\omega) \sim \mathcal{O}(1 \text{ MeV})$, which is again quite large for conventional charmonium assignment.

4.5 Charged Z states

The $Z^+(4430)$, the first charmonium-like state of non-zero electric charge, has been observed in the $\pi^+\psi(2S)$ decay channel in a study of $B \to K\pi^+\psi(2S)$ decays performed by Belle [41]. This observation, based on a simple fit to the $\pi^+\psi(2S)$ mass distribution, has been confirmed through the Dalitz-plot analysis of the $B \to K\pi^+\psi(2S)$ [42]. Being a charged state the $Z^+(4430)$ has minimum quark content $[c\bar{c}u\bar{d}]$, thus must be exotic. Theoretical explanations have suggested that it could be either an S-wave threshold effect or a $D^*\bar{D}_1(2420)$ molecule, whereas tetraquark hypothesis considers the $Z^+(4430)$ to be a diquark-antidiquark state with the $[cu][\bar{c}\bar{d}]$ configuration and predicts an existence of its neutral partner decaying to $\psi(2S)\pi^0$ or $\psi(2S)\eta$ [43]. In the molecular scenario the dominating decay modes should be $D^*\bar{D}^*\pi$ whereas in the tetraquark one: $D^{(*)}\bar{D}^*$ and $J\psi\pi$ decay channels in addition to $\psi(2S)\pi$.

Recently BaBar in a search for the $Z^+(4430)$ in the $\pi^+\psi(2S)$ and π^+J/ψ decays modes has not found significant $Z^+(4430)$ signal in any of these systems [44], but claims that both Belle and BaBar data remain statistically consistent. The upper limit on the branching fraction product measured by BaBar: $\mathcal{B}\left(\bar{B}^0 \to Z(4430)^+K^-\right)\mathcal{B}\left(Z^+ \to \psi(2S)\pi^+\right) < 3.1 \times 10^{-5}$ does not contradict Belle measurement of $3.2^{+1.8}_{-0.9}\,^{+5.3}_{-1.6} \times 10^{-5}$. This calls for further, high statistics studies of the $Z^+(4430)$. Two other charged resonance-like structures have been observed by Belle in the $\pi^+\chi_{c1}$ mass distribution near 4.1 GeV/c^2 in the $\bar{B}^0 \to K^-\pi^+\chi_{c1}$ decays through full analysis of the Dalitz plot [45]. Just like in the $Z^+(4430)$ case, both these states once confirmed will be certain candidates for exotic, most likely multiquark states.

5 Bottomonia

Experimental data on bottomonia remain incomplete. With respect to $c\bar{c}$ spectrum, studies of $b\bar{b}$ states require higher statistics, since resonances are expected to be broad, have many decay channels, and the cross sections are lower. In addition to completing the picture of conventional bottomonia also search for exotic states, $b\bar{b}$ analogues of the $c\bar{c}$-like exotic resonances would be a good test for the proposed interpretations.

Below the $B\bar{B}$ threshold the known states are $\Upsilon(1,2,3S)$, $\chi_{b1,b2,b3}(1P)$ and, since very recently also $\eta_b(1S)$ (reffered to as the η_b). The spin-singlet states, $\eta_b(2,3S)$ and $h_b(1,2,3P)$, are still missing and could be observed via magnetic or hadronic transitions from lower Υ states. The D-wave $b\bar{b}$ states $\psi_{b1,b2,b3}(1,2D)$ either have not been observed or need confirmation. Above the $B\bar{B}$ threshold only $\Upsilon(4,5,6S)$, vector states were found, though properties of the latter two are not measured precisely.

5.1 Discovery of the η_b

The ground state of bottomonium system, the η_b, has been discovered by BaBar in energy spectrum of the monochromatic photons from the radiative transition $\Upsilon(3S) \to \gamma\eta_b$ [46].

Such an inclusive approach suffers from a severe background; in addition to large non-peaking background from $e^+e^- \to q\bar{q}$ continuum and bottomonium decays, there is also a background peaking close to the signal region which is expected by theory around $E_\gamma = 900$ MeV. Such a background arises from two sources: double radiative decays $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$; $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ producing a dominant peak around 760 MeV, and a production of the $\Upsilon(1S)$ via ISR $e^+e^- \to \gamma_{ISR}\Upsilon(1S)$ leading to a peak near 860 MeV (Fig. 5). From the fit to the E_γ spectrum, with the mentioned backgrounds properly modelled, the signal peak has been observed at $E_\gamma = 921.2^{+2.1}_{-2.8} \pm 2.4$ MeV corresponding to the η_b mass of $9388.9^{+3.1}_{-2.3} \pm 2.7$ MeV/c^2. This gives hyperfine mass splitting between the η_b and $\Upsilon(1S)$ about 71 MeV/c^2, slightly larger than most potential models predictions [47]. BaBar has found also an evidence for the radiative transition $\Upsilon(2S) \to \gamma\eta_b$ [48] using a procedure similar to the study of $\Upsilon(3S)$ sample. The η_b mass measured to be $9392.9^{+4.6}_{-4.8} \pm 1.9$ MeV/c^2 is consistent with one from the discovery analysis.

Exclusive searches, which would allow one to measure the η_b width, will be difficult because dominant hadronic decays of the η_b are expected to proceed through OZI suppressed two gluons and, as such, will result in low branching fraction ($\mathcal{O}(10^{-5})$) and high multiplicity decays.

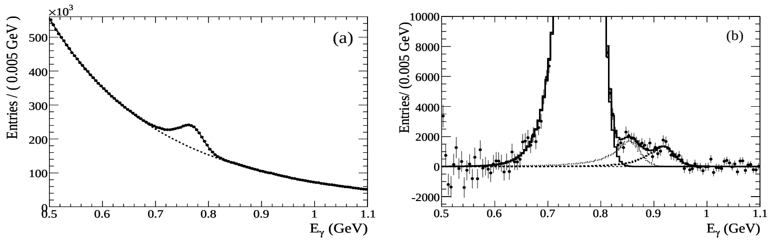

Figure 5: Inclusive spectrum of photons from $\Upsilon(3S) \to \gamma\eta_b$ before (left) and after (right) non-peaking background subtraction. The peaking components in right plot are from $\chi_{bJ}(2P)$, ISR $\Upsilon(1S)$ and η_b. In the left plot only the $\chi_{bJ}(2P)$ peak is visible.

5.2 Υ states

Recently new experimental data on the higher Υ states have been delivered by the B-Factories. Belle performed exclusive study of the $\Upsilon(5S)$ dipion transitions, whereas BaBar studied inclusive $b\bar{b}$ cross-section in the $\Upsilon(5S)$ and $\Upsilon(6S)$ mass region.

Belle has found unexpectedly large signals for the $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$) decays [49]. Their partial widths are of about $\mathcal{O}(100$ keV), thus about two orders of magnitude larger than for the other Υ states. Similar relation observed between $\Gamma(Y(4260) \to J/\psi\pi^+\pi^-)$ and such partial widths for usual charmonia, has suggested that this might be a $b\bar{b}$ analogue of $Y(4260)$ (Y_b) overlapping the $\Upsilon(5S)$ and giving the anomalous dipion transitions. To check this, Belle performed an energy scan between 10.83 GeV and 11.02 GeV and measured energy dependent cross section for the $\Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$) production (Fig. 6). It has revealed an enhancement which cannot be described by a conventional, confirmed by the inclusive R_b fit, $\Upsilon(5S)$ line shape. Fit to the exclusive cross sections yields a peak mass of $10889.6 \pm 1.8 \pm 1.5$ MeV/c^2 and a total width of $54.7^{+8.5}_{-7.2} \pm 2.5$ MeV/c^2 [50]. Explanation other than existence of the Y_b with mass of 10.89 GeV, suggests mixing of the conventional $b\bar{b}$ state with the threshold followed by rescattering to $\Upsilon(nS)\pi^+\pi^-$ [51].

BaBar has measured the R_b values in the range 10.54 to 11.20 GeV [52]. This measurement reveals a rich structure of $B^{(*)}\bar{B}^{(*)}$, and $B_s^{(*)}\bar{B}_s^{(*)}$ thresholds. To measure the parameters of the $\Upsilon(5S)$ and $\Upsilon(6S)$, one has performed a simplified fit with two Breit-Wigner resonances and a flat $b\bar{b}$ continuum added coherently (Fig. 6). The measured masses: $m_{\Upsilon(5S)} = 10.876 \pm 0.002$ GeV$/c^2$ and $m_{\Upsilon(6S)} = 10.996 \pm 0.002$ GeV$/c^2$ agree with the PDG values, whereas the widths: $\Gamma_{\Upsilon(5S)} = 43 \pm 4$ MeV$/c^2$, $\Gamma_{\Upsilon(6S)} = 37 \pm 3$ MeV$/c^2$ are significantly lower. However coupled channel effects and the thresholds mentioned, once taken properly into account, may modify the fit results. Also possible exotic extensions could be further tested in the fit model.

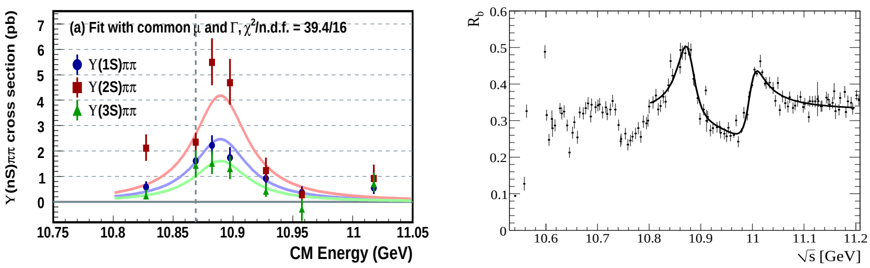

Figure 6: Left: Cross-section for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ processes from Belle. The curves show fit result, the vertical line indicates the $\Upsilon(5S)$ mass. Right: Fitted R_b from BaBar.

6 Beauty baryons

In the pre-LHC era Tevatron is the unique facility to study baryons containing b quark. Till recently the only b-baryon observed was Λ_b^0 (quark content $[udb]$); large Tevatron data sample made possible the observation of the Ξ_b^- $[dsb]$, the $\Sigma_b^{(*)}$ $[uub]$, $[ddb]$ and recently the doubly-strange b-baryon Ω_b^- $[ssb]$. In studies of Ω_b^- its decay chain: $\Omega_b^- \to J/\psi\Omega^-$, $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$ and $\Lambda \to p\pi^-$ was fully reconstructed. The $M(J/\psi\Omega^-)$ mass distribution measured for selected candidates by $D\emptyset$ is shown in Fig. 7 [53]. An observed peak, assumed to originate from the Ω_b^-, has a mass $6165 \pm 10 \pm 13$ MeV$/c^2$, slightly higher than a theory predicted Ω_b^- mass between $5.94 - 6.12$ GeV$/c^2$. The Ω_b^- production rate $f(b \to \Omega_b^-)\mathcal{B}(\Omega_b^- \to J/\psi\Omega^-)$, measured with respect to the production rate of baryon of similar topology $\Xi_b^- \to J/\psi\Xi^-$, is $0.80 \pm 0.32^{+01.4}_{-0.22}$. Position of a peak in the $M(J/\psi\Omega^-)$ obtained by CDF (Fig. 7) is measured to be $6054 \pm 7 \pm 1$ GeV$/c^2$ [54], thus significantly lower than the mass measured by $D\emptyset$. CDF also measured lifetime of the Ω_b^- to be $1.13^{+0.53}_{-0.40} \pm 0.02$ ps, in agreement with theory calculations giving $0.83 < \tau_{\Omega_b^-} < 0.67$ ps. The Ω_b^- production rate with respect to the Ξ_b^- has been measured to be $0.27 \pm 0.12 \pm 0.01$, thus lower than the one in $D\emptyset$ analysis.

Because of the different Ω_b^- mass measured by $D\emptyset$ and CDF, it is not clear whether both experiments see the same baryon. Further analysis for full Tevatron data sample is needed to resolve this discrepancy.

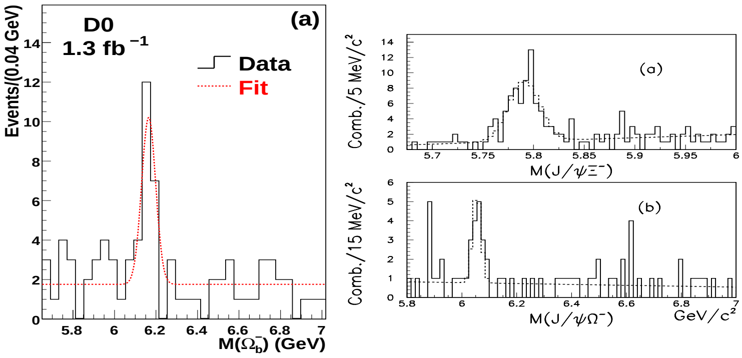

Figure 7: $M(J/\psi\Omega^-)$ distribution and fit result from $D\emptyset$ (left) and CDF (bottom right). Top right plot shows reference $M(J/\psi\Xi^-)$ distribution from CDF.

7 Summary

Spectroscopy of heavy flavour hadrons has attracted significant interest in recent years due to many experimental facilities such as BaBar, Belle, BES, Cleo, CDF and $D\emptyset$ reporting discoveries of new states, new production mechanisms and new decays. The XYZ particles, being candidates for exotic hadrons, may suggest that there is a new $c\bar{c}$ spectroscopy around 4 GeV mass region. Future experiments like BESIII, Panda, Super B-Factories will certainly bring new results in this field.

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Discussion

Ahmed Ali (DESY): I would like to make two comments. My first comment is that there is an indirect theoretical argument against X(3872) as a DD* molecule based on the recent work by Grinstein at al. Assuming that X(3872) is a DD* molecule, their estimation of the upper limit of the cross section for PPbar- ¿X(3872) + X is at least two order of magnitude lower than the CDF measurement. My second comment is actually a suggestion to take a closer look in the energy range from ^{2} f(5S) to 12 GeV searching for bbbar -¿ states of the tetraquarks type.

Answer: As for the first comment from Prof. Ali, indeed if the X(3872) was a DD* molecule its prompt production from pp-bar annihilation should be very suppressed. Simply speaking, largely separated D and D* mesons would not have enough time to form a J/psipipi final state in which the X(3872) has been reconstructed by CDF. However an interpretation of X(3872) as a molecule with an admixture of charmonium component, proposed recently by theoreticians, might explain the large cross-section measured.

Regarding the second comment, in the inclusive bb-bar cross-section measured by BaBar there are couple of spikes sticking out of a line fitted with only the Upsilon states assumed. They can be either just statistical fluctuations or indicate an existence of new states below 11GeV. However the energy scans taken by Belle in new runs in 2010 do not confirm any narrow peaks in hadronic cross-section in the range from 10.7 to 11 GeV. Nevertheless studying of exclusive cross-sections might be more promising. An example is cross-section for bb-bar -¿Y(1,2,3S)pi+pi- around 10.9GeV, found by Belle to be far too large for being produced from conventional bb-bar state.

Rob Kutschke (FNAL): How do you tell the difference between the molecule state and the hybrid state? I am thinking of the case in which the isospin partners are not seen but in which there are reasons to believe that the isospin partners are unbound. Are there observables with which to distinguish the two interpretations?

Answer: In the mentioned case measuring of quantum numbers through study of angular distributions, could help to distinguish between molecules and hybrids. Hybrids are allowed to have exotic spin-parities. Studying certain final states could give some information as well; hadronic transitions should dominate for hybrids, whereas decays to constituent mesons are expected to be dominant for molecules. Moreover a final state with an unbalanced flavour, for example strangeness, is not allowed for hybrids but possible for molecules.