Exotic hadron spectroscopy

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1 Introduction

The recent discovery of several charmonium and charmonium-like resonances indicates a renaissance of the $c\bar{c}$ spectroscopy. Majority of these observations have been enabled by the large data samples provided by the B-factories at SLAC and at KEK. Many of these so called XYZ states do not fit the conventional $c\bar{c}$ spectrum which is described, so far successfully, by the quark models. This suggests that some of them might be exotic i.e. be non-$q\bar{q}$ forms of hadrons. In this review the recent experimental evidences of possible exotic states are presented along with discussion on their interpretations proposed.

2 Phenomenology introduction

In the constituent quark model hadrons are classified either as mesons formed from quark-antiquark pairs or baryons consisting of three-quark triplets. Forces binding of quarks into hadrons are described by QCD. The potential models incorporating the general features of QCD describe the spectra and properties of the hadrons. In these models quarkonium states are described as quark-antiquark pair bound by single-gluon-exchange dominating at a short distance plus a linear confining potential linearly increasing as the quark separation increases. Adding the higher order corrections allows ones to obtain a picture of quarkonium multiplets including masses of resonances, their transitions, decays, etc. The low lying $c\bar{c}$ states being discovered over past years have properties that agree quite well with the models' predictions.

The QCD-motivated models predict 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[1].

Molecular state [1] consists of two mesons weakly bound through pion exchange to form a molecule. Consequence of a loose binding of the comprising mesons is that they tend to decay as if they are free. Molecules are generally not isospin eigenstates.

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[1] Pentaquarks are not discussed here as there have been no recent experimental results

Tetraquark is a tightly bound four-quark state of for example diquark-diantiquark configuration [2] where the comprising quarks group into colour-triplet scalar and vector clusters interacting dominantly by a gluon exchange. Strong decay proceeds through quark's rearrangement to form colour-singlet mesons followed by their dissociation. The $c\overline{c}$ multiquarks which could be easily distinguished from conventional $c\overline{c}$ are those of non-zero charge or/and strangeness like for example $[cd\overline{cu}]$, $[cd\overline{cs}]$.

Hybrid mesons [3] are states which in addition to quarkonium contain an excited gluon and are described by the flux-tube model [4]. The lowest excitations of potential produced by gluons lead to octet of the lowest mass hybrids; some of them bear exotic quantum numbers like $J^{PC} = 0^{+-}, 1^{-+}, 2^{+}$, which are not possible for conventional states. Observation of state of such spin-parity would indicate existence of an exotic resonance. The lowest charmonium hybrids are predicted by lattice QCD to have masses of about $4.2\mathrm{GeV}/c^2$, whereas their dominant decays are expected to be open charm decay including P-wave meson in final state e.g. $D\overline{D}^{**}$ dominating over $D\overline{D}^{(*)}$, and hadronic transition to charmonium via emission of light hadrons: $c\overline{c}+\pi\pi/\eta$, etc.

In addition, **thresholds** can also result in structures in cross-sections. At the threshold, for example $D^{(*)}\overline{D}^{(*)}$, states with small relative momentum may interact by exchanging pions. Such an attractive interaction can lead to the molecules mentioned; any repulsive interaction could give rise to a virtual state above threshold [5].

The conventional charmonium spectrum is much cleaner with regard to dense spectrum of light states, therefore exotic states containing $c\overline{c}$ 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.

3 Experimental opportunities for spectroscopy

The discoveries described in this review have been in the first place enabled by the two B-factories: PEPII at SLAC and KEKB at KEK. Both are e^+e^- asymmetric-energy colliders operating most of the time at the $\Upsilon(4S)$ mass (10.58 GeV). The results presented are based on the large data samples collected by the BaBar detector at the PEPII and the Belle detector at the KEKB. The current data sample accumulated at the $\Upsilon(4S)$ by Belle amounts to about $730\mathrm{fb}^{-1}$ and by BaBar: $430\mathrm{fb}^{-1}$. Many precious measurements come also from the other experiments: CLEO at the e^+e^- collider CESR in Cornell, the CDF and $D\emptyset$ at the $p\overline{p}$ collider Tevatron in Fermilab.

Although the B-factories were primarily constructed to study the CP-violation in B meson decays, their unexpected bonus has been an significant experimental input to the hadron spectroscopy especially to the charmonia. At the B-factories the $c\overline{c}$ states can be produced in numerous production mechanisms such as B meson decays, initial state radiation, double $c\overline{c}$ production and two-photon collisions.

The simplest B **meson decays** yielding charmonium state ($X_{c\bar{c}}$) are $B \to K X_{c\bar{c}}$. They are described by the Cabibbo-favoured $b \to c\bar{c}s$ transition, and thus have large branching fractions ($\mathcal{O}(10^{-3})$) assuring large number of detected charmonia. Decays of this type favour production of charmonia bearing $J^{PC} = 0^{++}$, 1^{--} and 1^{++}, while known quantum numbers of parent B meson allow ones to determine further the spin-parity of the produced $X_{c\bar{c}}$ by performing angular analysis.

Initial state radiation (ISR) process corresponds to the case when the initial e^+ or e^- radiates photon(s) making the center-of-mass (cm) energy of e^+e^- annihilation accordingly reduced. If an energy of radiated γ is large enough then e^+e^- annihilation occurs at the energy being within a range of charmonium masses and allows producing charmonia bearing spin-parity of photon i.e. $J^{PC} = 1^{--}$. Although the ISR is a higher-order QED process suppressed by α_{em}, the very high luminosities of the B-factories effectively compensate it.

Double charmonium production $e^+e^- \to X_{c\bar{c}}Y_{c\bar{c}}$ has been found to have much larger cross section than QCD originally predicted. Therefore some of these processes like an inclusive J/ψ production $e^+e^- \to J/\psi X$, occur to be useful for the charmonium spectroscopy, as it is quite likely that system X recoiling against J/ψ is a charmonium state. Because of C-parity conservation, only $c\bar{c}$ states with $C = +$ are produced in association with J/ψ.

Two-photon collisions are produced when both an initial e^+ and e^- emit photons which afterwards interact with each other. Such $\gamma\gamma$ interactions can produce states with $J^{PC} = 0^{-+}$, 0^{++}, 2^{-+} and 2^{++}.

4 Experimental evidence

4.1 $X(3872)$: $c\bar{c}$ like state

In 2003 Belle observed the $X(3872)$ as a narrow peak in the $M(J/\psi\pi^+\pi^-)$ spectrum in $B^+ \to K^+\pi^+\pi^- J/\psi$ decays [6]. The state has been confirmed by CDF and $D\emptyset$ to be produced in $p\bar{p}$ collisions, as well as by BaBar [7]. The current PDG values for the $X(3872)$ mass and upper limit for its total widths are $m_{X(3872)} = 3871.4 \pm 0.6$ MeV/c^2 and $\Gamma_{X(3872)} < 2.3$ MeV/c^2 respectively [8]. Recently the CDF experiment has precisely measured mass of the $X(3872)$ to be $m_{X(3872)} = 3871.61 \pm 0.16 \pm 0.19$ MeV/c^2 (Fig. 1). In addition to $J/\psi\pi^+\pi^-$ where dipion mass spectrum (Fig. 1) is consistent with originating from $\rho \to \pi\pi$ [9], also evidence of the $X(3872) \to J/\psi\pi^+\pi^-\pi^0$ mode proceeding via virtual $\omega \to \pi^+\pi^-\pi^0$ has been found [10]. Comparable rates of these decay modes suggest large isospin violation. Also, an evidence of radiative decays to $J/\psi\gamma$ [10] and recently to $\psi(2S)\gamma$ [11] indicates C-parity$= +$ for the $X(3872)$. The mentioned properties along with results of the CDF angular analysis [12] strongly favour $J^{PC} = 1^{++}$ and 2^{-+} for the $X(3872)$. As finding charmonium assignment fitting the $X(3872)$ is very unlikely, exotic interpretations have been suggested.

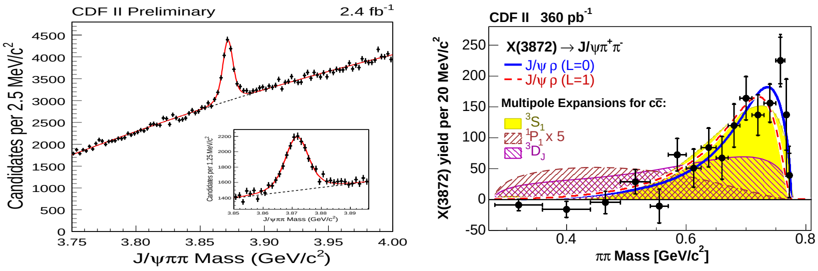

Figure 1: $M(J/\psi\pi^+\pi^-)$ distribution (left) and $M(\pi^+\pi^-)$ spectrum (right) for the X(3872) from CDF.

The $X(3872)$ mass being in close vicinity of the sum of the D^0 and D^{*0} masses ($m_{D^0} + m_{D^{*0}} = 3871.81 \pm 0.36$ MeV$/c^2$) has triggered speculations that $X(3872)$ is a molecular bound state of D^0 and $\overline{D}^{*0}$ lying just below the D^0D^{*0} threshold [13]. Dominating decay modes of such molecule are expected to be $D^0\overline{D}^0\pi^0$ and $D^0\overline{D}^0\gamma$ i.e. proceeding through its constituent D^{*0} decay; also admixtures of $J/\psi\rho/\omega$ are expected. A narrow near-threshold enhancement which could originate from the $X(3872)$, have been observed in the mass distribution of $D^0\overline{D}^{*0}$ system produced in the $B \to KD^0\overline{D}^{*0}$ decays (Fig. 2) [14]. Its mass measured by BaBar to be $m = 3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV$/c^2$ is slightly larger than one of the $X(3872) \to J/\psi\pi\pi$. However a new Belle measurement gives $m = 3872.6^{+0.5}_{-0.4} \pm 0.4$ MeV$/c^2$ being in good agreement with the current world average for the $X(3872)$ mass. Branching fraction of $X(3872) \to D^0\overline{D}^{*0}$ has been measured to be one order of magnitude larger than for $X(3872) \to J/\psi\pi^+\pi^-$; this supports the molecular interpretation of $X(3872)$. Although the resonance line-shape can be important for investigating the nature of the $X(3872)$ [15], studying the $X(3872)$ shape is not feasible with the current statistics. The Flatté parameterization tried for description of the $D^0\overline{D}^{*0}$ threshold enhancement gives similar results as the Breit-Wigner function (Fig. 2).

Tetraquark explanation of $X(3872)$ [2] [16] predicts that the neutral doublet should exist corresponding to $[cu][\overline{cu}]$ and $[cd][\overline{cd}]$ states of which former, identified with the $X(3872)$, is produced in charged $B^+ \to K^+J/\psi\pi^+\pi^-$ decays, whereas the latter should be observed in neutral $B^0 \to K^0J/\psi\pi^+\pi^-$ decays and have mass differing by a few MeV from the $X(3872)$. However recent studies have not revealed any significant mass difference between the X produced in charged versus neutral B decays [17]: BaBar measured $\delta m = 2.7 \pm 1.6 \pm 0.4$ MeV$/c^2$ whereas Belle: $\delta m = 0.18 \pm 0.89 \pm 0.26$ MeV$/c^2$ (Fig. 3). An interpretation of the peak observed in $D^0\overline{D}^{*0}$ as a missing, heavier partner of the $X(3872)$ [18] has also failed for its mass from the new Belle study is consistent with the $X(3872)$. Charged partner of the $X(3872)$ predicted by the tetraquark models in the $J/\psi\pi^+\pi^0$ has not been observed so far [19].

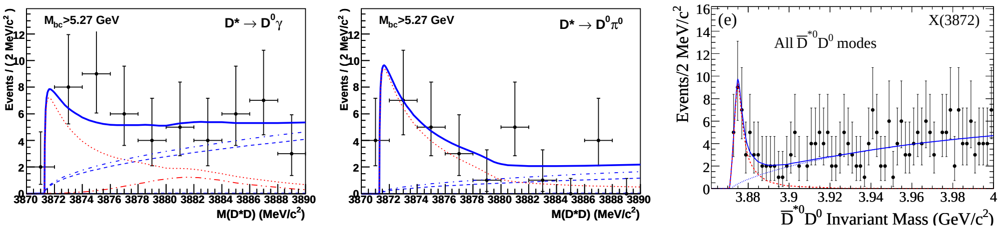

Figure 2: $M(D^0\overline{D}^{*0})$ distributions for $B \to KD^0\overline{D}^{*0}$ decays; left and middle plots are for $D^{*0} \to D^0\gamma$ and $D^{*0} \to D^0\pi^0$ from Belle; right one is BaBar plot for both D^{*0} modes combined. Red-dotted line in Belle plots is fit result with the Flatté parameterization used, blue-solid line is fit using the Breit-Wigner function.

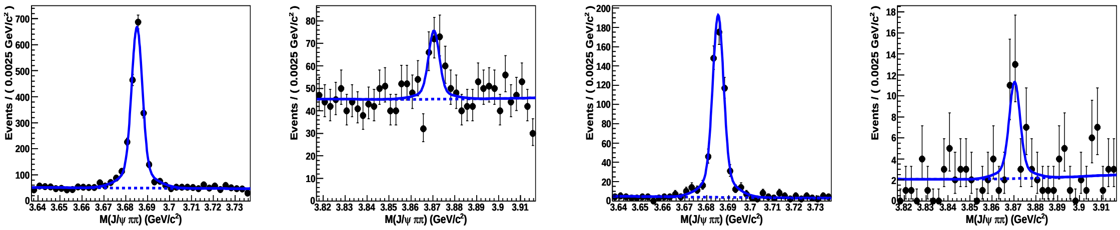

Figure 3: $M(J/\psi\pi^+\pi^-)$ distribution for the $\psi(2S)$ (used as a reference) and $X(3872)$ regions for charged $B \to KJ/\psi\pi^+\pi^-$ decays (respectively first and second plots to the left) and for neutral ones (third and fourth plots).

Thus, in view of the mentioned experimental results, the molecular interpretation of the $X(3872)$ seems to be favorable.

4.2 Charged charmonium-like Z states

The first charmonium-like state of non-zero electric charge has been observed in the $\pi^+\psi(2S)$ decay channel in a study of the $B \to K\pi^+\psi(2S)$ decays [20]. In the Dalitz plot shown in Fig. 4 there are vertical clusters visible corresponding to the mesons in the $K\pi^+$ final state like $K^*(892)$, $K_0^*(1430)$, $K_2^*(1430)$, whereas an unexpected horizontal band comes from the state in the $\pi^+\psi(2S)$ system, called the $Z^+(4430)$. The $M(\pi^+\psi(2S))$ projection after the K^* mass regions being excluded (Fig. 4) exhibits a narrow peak; its Breit-Wigner mass and width obtained from the fit to this projection are: $m_{Z^+(4430)} = 4433 \pm 4 \pm 2$ MeV$/c^2$ and $\Gamma_{Z^+(4430)} = 45^{+18}_{-13}\,^{+30}_{-13}$ MeV$/c^2$ respectively. It has been checked that the observed peak is not a reflection from any known states and it is too narrow to be produced by any interferences between the $K\pi^+$ mesons. The statistics available have not been large enough to determine the spin-parity of

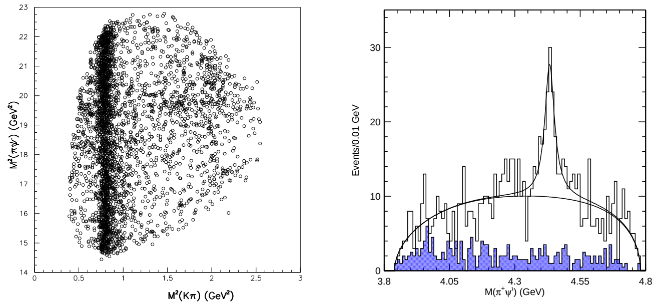

Figure 4: $M^2(\pi^+\psi(2S))$ vs. $M^2(K\pi^+)$ Dalitz plot distribution for $B \to K\pi^+\psi(2S)$ decays and its $M(\pi^+\psi(2S))$ projection with the K^* mass regions vetoed.

the $Z^+(4430)$ though.

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 since the mass of the $Z^+(4430)$ is close to the $D^*\overline{D}_1(2420)$ threshold it could be either an S-wave threshold effect [21] or a $D^*\overline{D}_1(2420)$ molecule [22], whereas tetraquark hypothesis considers the $Z^+(4430)$ to be a diquark-antidiquark state with the $[cu][\bar{c}\bar{d}]$ configuration [23] and predicts an existence of its neutral partner decaying to $\psi(2S)\pi^0$ or $\psi(2S)\eta$. In the molecular scenario the dominating decay modes should be $D^*\overline{D}^*\pi$ whereas in the tetraquark one: $D^{(*)}\overline{D}^*$, $J\psi\pi$ and $\psi(2S)\pi$.

Recently BaBar in their search for the $Z^+(4430)$ in the $\pi^+\psi(2S)$ and π^+J/ψ decays modes have not found significant $Z^+(4430)$ signal in any of the systems studied [24]. This calls for further studies to be resumed by both Belle and BaBar as well as other experiments.

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 $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ decays through full analysis of its Dalitz plot (Fig. 5). In addition to the resonances decaying into $K^-\pi^+$, adding two states in the $\pi^+\chi_{c1}$ system has been necessary to obtain acceptable quality of the Dalitz plot fit. These so called Z_1 and Z_2 states have significance exceeding 5σ and their masses and total widths are respectively: $m_{Z_1} = 4051 \pm 14^{+20}_{-41}$ MeV/c^2, $\Gamma_{Z_1} = 82^{+21}_{-17}{}^{+47}_{-22}$ MeV/c^2, $m_{Z_2} = 4248^{+44}_{-29}{}^{+180}_{-35}$ MeV/c^2, and $\Gamma_{Z_2} = 177^{+54}_{-39}{}^{+316}_{-61}$ MeV/c^2. Both $J = 0$ and 1 spin hypotheses tested have resulted in similar qualities of the Dalitz plot fit, therefore quantum numbers of the Z_1 and Z_2 have not been determined. The $M(\pi^+\chi_{c1})$ distribution for $1.0 < M^2(K^-\pi^+) < 1.75$ GeV$^2/c^4$ where the contributions of the Z_1 and Z_2 are most clearly seen is shown in Fig. 5. Just like in the $Z^+(4430)$ case, both these states once confirmed will be certain candidates for exotic, most likely multiquark states.

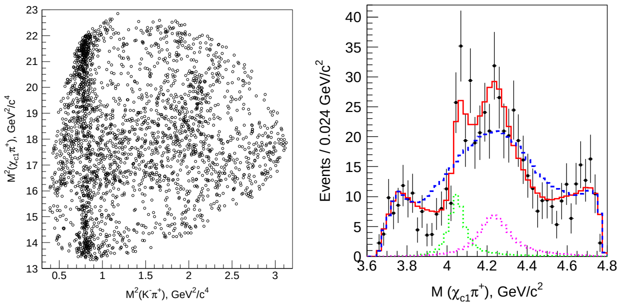

Figure 5: Left: $M^2(\pi^+\chi_{c1})$ vs. $M^2(K\pi^+)$ Dalitz plot distribution for $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ decays. Right: $M(\pi^+\chi_{c1})$ distribution for $1.0 < M^2(K^-\pi^+) < 1.75\ \mathrm{GeV}^2/c^4$. Blue histogram is the Dalitz plot fit result for the model with all known K^*'s and without any $\chi_{c1}\pi^+$ resonance; red histogram represents the fit result with all known K^*'s and two $\pi^+\chi_{c1}$ resonances; green and magenta histograms represent the contributions of the $\pi^+\chi_{c1}$ resonances.

4.3 Family of the 1^{--} Y states

First member of the family, dubbed $Y(4260)$, was discovered by BaBar in the $J/\psi\pi^+\pi^-$ system produced in the ISR radiation process [28]. Fit to the observed peak with a single Breit-Wigner parameterization (Fig. 6) yields a mass $m_{Y(4260)} = 4259 \pm 8^{+2}_{-6}$ MeV/c^2 and a full width $\Gamma_{Y(4260)} = 88 \pm 23^{+6}_{-4}$ MeV/c^2. BaBar also found a broad peak around 4.32 GeV/c^2 in $e^+e^- \to \psi(2S)\pi^+\pi^-$ cross-section (Fig. 6) with parameters distinct from the $Y(4260)$ [30].

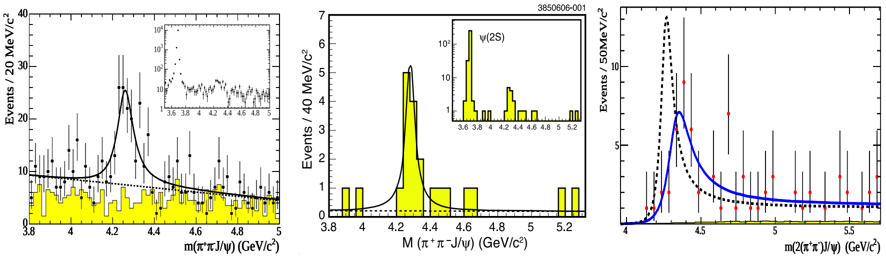

Figure 6: $M(J/\psi\pi^+\pi^-)$ distribution from BaBar (left) and CLEO (middle) and $M(\psi(2S)\pi^+\pi^-)$ distribution from BaBar (right).

The $Y(4260)$ has been confirmed by CLEO [27] and both structures have been observed also by Belle [29] [31]. However Belle in their studies of the cm energy dependent cross-sections for $e^+e^- \to J/\psi\pi^+\pi^-$ and $e^+e^- \to \psi(2S)\pi^+\pi^-$ observed double-peak structures in each of these systems rather than just single peaks (Fig. 7).

Fit to the $M(J/\psi\pi^+\pi^-)$ with two coherent Breit-Wigner functions gives parameters of the $Y(4008)$ and $Y(4260)$ to be: $m_{Y(4008)} = 4008\pm40^{+114}_{-28}$ MeV/c^2, $\Gamma_{Y(4008)} = 226\pm44\pm87$ MeV/c^2 and $m_{Y(4260)} = 4247\pm12^{+17}_{-32}$ MeV/c^2, $\Gamma_{Y(4260)} = 108\pm19\pm10$ MeV/c^2. The parameters of the $Y(4260)$ agree well with the BaBar results; the $Y(4008)$, seen for the first time, has not been confirmed in the recent BaBar study [24]. Fit with similar parameterization applied to the $M(\psi(2S)\pi^+\pi^-)$ yields masses and total widths of the so called $Y(4360)$ and $Y(4660)$ states: $m_{Y(4360)} = 4361\pm9\pm9$ MeV/c^2, $\Gamma_{Y(4360)} = 74\pm15\pm10$ MeV/c^2 and $m_{Y(4660)} = 4664\pm11\pm5$ MeV/c^2, $\Gamma_{Y(4660)} = 48\pm15\pm3$ MeV/c^2. The $Y(4360)$ is consistent with the mentioned peak around 4.32 GeV/c^2 seen by BaBar, whereas the $Y(4660)$ is a new member of the Y family.

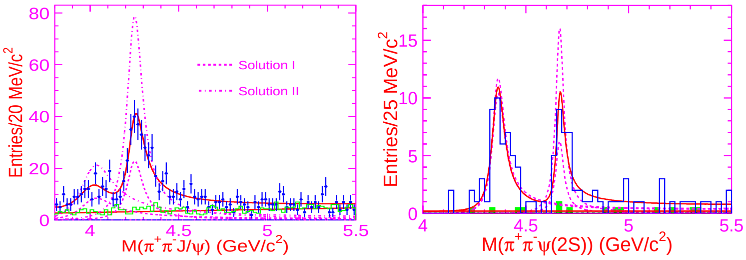

Figure 7: $M(J/\psi\pi^+\pi^-)$ (left) and $M(\psi(2S)\pi^+\pi^-)$ (right) distributions from Belle. The dashed curves show the Y state contributions for the two fit solutions corresponding to the destructive and constructive interferences between the resonances.

All these Y states, as observed through ISR, have $J^{PC} = 1^{--}$. They parameters do not coincide with any of the vector charmonia observed so far in corresponding mass region ($\psi(4040)$, $\psi(4160)$, $\psi(4415)$) 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 $D\overline{D}$, $D\overline{D}^*$ or $D^*\overline{D}^*$, there are no clear peaks in the cross-sections for $e^+e^- \to D^{(*)}\overline{D}^{(*)}$ [32] that could correspond to the Y states. Instead, their partial decay widths for the hadronic transitions to $J/\psi\pi\pi$ or $\psi(2S)\pi\pi$ are very large ($\mathcal{O}$(MeV)) and thus unlikely for the conventional $c\bar{c}$ states. Other possible interpretations of the Y states include: charmonium hybrids predicted in this mass region and expected to decay dominantly into $D\overline{D}_1$; $cq\overline{cq}$ tetraquarks, $D^*\overline{D}^*$, $D\overline{D}_1$ and $D^*\overline{D}^*_0$ molecules or just S-wave charm meson thresholds. Moreover coupled-channel effects, rescattering of pairs of charmed mesons, interference of channels near threshold with the conventional charmonia, once understand by theory, could give better insight into the nature of the structures observed. Also, more experimental information on the decay properties is needed, 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 $D\overline{D}_1$.

In addition to interpretations of the exotic candidates observed in the $c\bar{c}$ system, the models also predict the analogous states in the $b\bar{b}$ and $s\bar{s}$ systems. Recent experimental results seem to support these predictions.

Belle using their data sample collected at the $\Upsilon(5S)$ mass (10.87 GeV), studied dipion transitions of the $\Upsilon(5S)$ and found unexpectedly large signals for the $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ channels [33]. The corresponding partial widths measured are: $\Gamma(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-) = 590 \pm 40 \pm 90$ keV, $\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-) = 850 \pm 70 \pm 160$ keV. They are more than two orders of magnitude larger than corresponding partial widths for the other Υ's. This is a similar relation as observed for the $\Gamma(Y(4260) \to J/\psi\pi^+\pi^-)$ with regard to the partial widths for the conventional $c\bar{c}$. Possible interpretation is that $b\bar{b}$ analogous of $Y(4260)$, called Y_b, is overlapping the $\Upsilon(5S)$ and is a source of the anomalous dipion transitions.

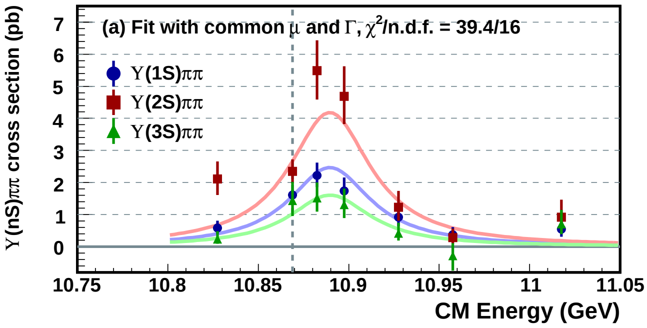

Figure 8: The cm energy dependent cross-section for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ processes. The curves show fit result, the vertical line indicates the $\Upsilon(5S)$ mass.

To check this hypothesis, Belle performed an energy scan between 10.83 GeV and 11.02 GeV. Indeed, the measured energy dependent cross-section for the $\Upsilon(nS)\pi^+\pi^-$ ($n = 1, 2, 3$) production (Fig. 8) has revealed an enhancement which cannot be described by the conventional $\Upsilon(5S)$ lineshape. Fit using a single Breit-Wigner resonance shape 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 [34]. Explanation other than existence of the Y_b, suggests mixing of the conventional $b\bar{b}$ with the threshold followed by rescattering to $\Upsilon(nS)\pi^+\pi^-$ [35].

4.4 Other XYZ around 4 GeV

The $Y(3940) \to J/\psi\omega$ in $B \to KJ/\psi\omega$ decays was observed by Belle [36] and recently confirmed by BaBar [37] although a mass and a total width of the $Y(3940)$ 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 (Fig. 9) ($m_{Y(3940)} = 3914.6^{+3.8}_{-3.4} \pm 2$ MeV/c^2, $\Gamma_{Y(3940)} = 34^{+12}_{-8} \pm 5$ MeV/c^2) slightly differ. Large production rates in B decays ($\mathcal{O}(10^{-5})$) imply $\Gamma(Y(3940) \to J/\psi\omega) > 1$ MeV/c^2, which is larger than for any conventional $c\bar{c}$ above open charm threshold. However the $\chi_{c1}(2P)$ charmonium assignment, suggested by the mass and width of the $Y(3940)$, cannot be excluded. This can be tested by searching for the $D\overline{D}^*$ decay mode which should dominate for $\chi_{c1}(2P)$. Possible explanation for the strong $J/\psi\omega$ decay mode is rescattering through $D\overline{D}^* \rightarrow J/\psi\omega$.

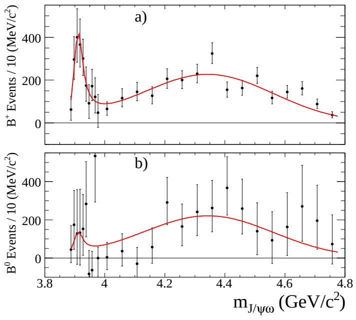

Figure 9: $M(J/\psi\omega)$ distributions from BaBar for charged (top) and neutral (bottom) $B \rightarrow KJ/\psi\omega$ decays.

The $X(3940) \rightarrow D\overline{D}^*$ and $X(4160) \rightarrow D^*\overline{D}^*$ states have been observed in double charmonium production in association with the J/ψ: $e^+e^- \rightarrow J/\psi D^{(*)}\overline{D}^{(*)}$ [39]. As the $X(3940) \rightarrow J/\psi\omega$ decays have not been observed, it is unlikely that $X(3940)$ and $Y(3940)$ are the same state. As the production of $J = 0$ resonances seems to be favoured over charmonia with a higher spin [38], thus likely assignment for these X states could be $\eta_c(3S)$ and $\eta_c(4S)$. However measured masses of the X states: $m_{X(3940)} = 3942^{+7}_{-6} \pm 6$ MeV/c^2 and $m_{X(4160)} = 4156^{+25}_{-20} \pm 15$ MeV/c^2, are significantly lower then masses predicted by the potential models for the $\eta_c(3S)$ and $\eta_c(4S)$ (respectively 4050 and 4400 MeV/c^2). This η_c assignment could be tested by performing an angular analysis and searching for these states in $\gamma\gamma \rightarrow D^{(*)}\overline{D}^{(*)}$.

5 Summary

As it has been presented, there have been many so called XYZ states observed which cannot be easily accommodated within the conventional $c\bar{c}$ multiplets and are good candidates for exotic hadrons like molecules, tetraquarks or hybrids. This may suggest that there is a new $c\bar{c}$ spectroscopy around 4 GeV mass region. Also there is experimental evidence that similar states may exist in other quark sectors for example in the $b\bar{b}$.

However there are still many issues to be further studied by both experiment and theory to prove that the XYZ states are not conventional ones. The most urgent are: confirmation of the states by other experiments, measurement their quantum numbers and searching for other decay modes. Whereas from the theory side better understanding of the thresholds and coupled channel effects is necessary.

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