Searches for, and Properties of, New Charmonium-like states

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We review the recent *B*-factory measurements of new states which, in some cases, exhibit Charmonium-like properties, and in other cases suggest the existence of a new spectroscopy. Several theoretical interpretations of the new states have come to the fore although, at time of writing, we are no closer to untangling the nature of most of the particles making up the observed new zoo of states.

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1. Introduction

Although the Standard Model of elementary particles is well established, strong interactions are not yet fully under control. We believe QCD is the field theory capable of describing them, but we are not yet capable, in most cases, to make exact predictions. Systems that include heavy quark-antiquark pairs (quarkonia) are an ideal and unique laboratory to probe both the high energy regimes of QCD, where an expansion in terms of the coupling constant is possible, and the low energy regimes, where non-perturbative effects dominate.

Recently, this field has experienced a rapid expansion with a wealth of new data coming in from diverse sources: data on quarkonium formation from dedicated experiments (BES at BEPC, KEDR at VEPP-4M CLEO-c at CESR), clear samples produced by high luminosity *B*-factories (PEP-II and KEKB), and very large samples produced from gluon-gluon fusion in p$\bar{\text{p}}$ annihilations at the Tevatron (CDF and D0 experiments).
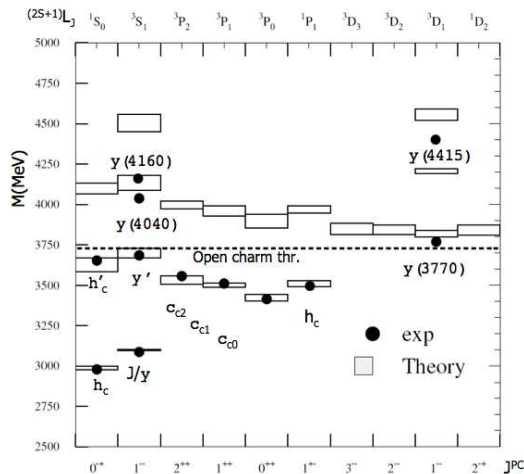

Figure 1: Charmonium states with $L <= 2$. The theory predictions are according to the potential models described in Ref. [1].

This paper will be devoted to reviewing the experimental evidence of new states that might be aggregations of more than just a quark-antiquark pair. Although the possibility of bound states of two quarks and two antiquarks or of quark-antiquark pairs and gluons has been predicted since the very start of the quark model [2], no observed state has yet been attributed to one of them: such an achievement would be a major step in the understanding of the strong interaction.

Currently the most credible explanations for the possible states, beyond the mesons and the baryons, are (find a full review in [1]):

- hybrids: bound states of a quark-antiquark pair and a number of gluons. The lowest lying state is expected to have quantum numbers $J^{PC} = 0^{+-}$. The impossibility of a quarkonium state to assume these quantum numbers (see below) makes this a unique signature for hybrids. Alternatively, a good signature would be the preference to decay into a quarkonium and a state that can be produced by the excited gluons (e.g. $\pi^+\pi^-$ pairs).

- molecules: bound states of two mesons, usually represented as $[Q\bar{q}][q'\bar{Q}]$, where Q is the heavy quark. The system would be stable if the binding energy would set the mass of the states below the sum of the two meson masses. While this could be the case for when $Q = b$, this does not apply for $Q = c$, where most of the current experimental data are. In this case the two mesons can be bound by pion exchange. This means that only states decaying strongly into pions can bind with other mesons (e.g. there could be D^*D states), and that the bound state could decay into it's constituents.

- tetraquarks: a quark pair bound with an antiquark pair, usually represented as $[Qq][\bar{q'}\bar{Q}]$. A full nonet of states is predicted for each spin-parity, i.e. a large number of states are expected. There is no need for these states to be close to any threshold.

In pursuing a further understanding of these states one must also beware of threshold effects, where am-

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Table I Most recent determination of the $J^{PC} = 1^{--}$ charmonium states from BES [3], compared to the 2006 edition of the PDG [4]

		$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M	PDG2006	3771.1 ± 2.4	4039 ± 1.0	4153 ± 3	4421 ± 4
(MeV/c^2)	BES '07	3771.4 ± 1.8	4038.5 ± 4.6	4191.6 ± 6.0	4415.2 ± 7.5
Γ_{tot}	PDG2006	23.0 ± 2.7	80 ± 10	103 ± 8	62 ± 20
(MeV)	BES '07	25.4 ± 6.5	81.2 ± 14.4	72.7 ± 15.1	73.3 ± 21.2

plitudes might be enhanced when new hadronic final states become possible.

Herein, we summarize the latest findings on the spectroscopy of the known heavy quarkonium states and the state of the art of the understanding of other states which might not fit in the ordinary spectroscopy.

2. Heavy quarkonium spectroscopy

The heavy quark inside these bound states has low enough energy that the corresponding spectroscopy is close to the non-relativistic interpretations of the atoms. The quantum numbers that are more appropriate to characterize a state are therefore, in decreasing order of energy splitting among different eigenstates, the radial excitation (n), the spatial angular momentum L, the spin S and the total angular momentum J. Given this set of quantum numbers, the parity and charge conjugation of the states are derived by $P = (-1)^{(L+1)}$ and $C = (-1)^{(L+S)}$. Figure 1 shows the mass and quantum number assignments of the well established charmonium states.

2.1. Charmonium spectroscopy

Figure 1 shows that all the predicted states below open charm threshold have been observed, leaving the search open only to states above the threshold. In this field the latest developments concern the measurement of the paramaters and the quantum number assignment for the $J^{PC} = 1^{--}$ states.

The BES collaboration has recently performed a fit to the R scan results which takes into account interference between resonances more accurately [3]. The updated parameters are reported in Tab. I, compared with the most recent determinations.

The $J^{PC} = 1^{--}$ assignment does not unambiguously identify the state, since both $^{2S+1}L_J = {}^3D_1$ and $^3D_1$ states would match it. The recent observation from Belle of the first exclusive decay of the $\psi(4415) \rightarrow DD_2^*(2460)$ [5], shows that this meson is predominantly D wave. At the same time the study from CLEO-c of the $\psi(3770) \rightarrow \chi_{cJ}\gamma$ [6] confirms the

dominance of the D wave also in this meson. Both these assignments confirm the theoretical predictions as shown in Fig. 1.
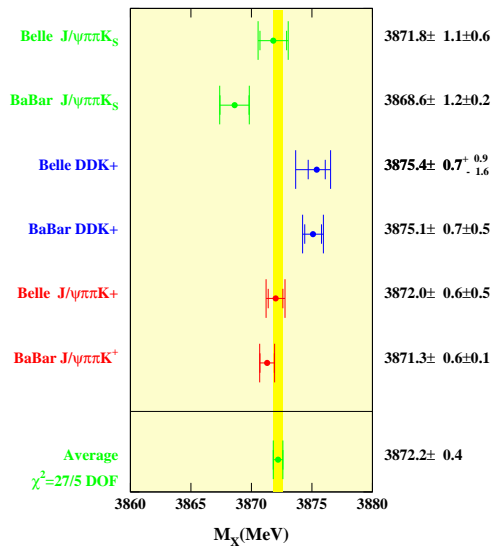

Figure 2: *Measured mass of the $X(3872)$ particle. The different production modes ($B^0 \rightarrow XK_S$ and $B^- \rightarrow XK^-$) and the different decay modes ($X \rightarrow J/\psi\pi\pi$ and $X \rightarrow D^{*0}D^0$) are separated.*

3. Non-standard charmonium states

3.1. The $X(3872)$

The $X(3872)$ was the first state that was found not to easily fit charmonium spectroscopy. It was initially observed decaying into $J/\psi\pi^+\pi^-$ with a mass just beyond the open charm threshold [7]. The $\pi^+\pi^-$ invariant mass distribution preferred the hypothesis of a $X(3872) \rightarrow J/\psi\rho$ decay, which would have indicated that if this were a charmonium state, the decay would have violated isospin. Since it would be quite unusual to have the dominant decay to be isospin violating, a search of the isospin partner $X^+ \rightarrow J/\psi\rho$ was conducted in vain by BaBar [8]. In the meanwhile the

decay $X \to J/\psi\gamma$ was observed [9], implying positive intrinsic charge conjugation.

The most recent developments concern the final assessment of the J^{PC} of this particle and the indication that the $X(3872)$ is actually a doublet. The CDF collaboration has performed the full angular analysis of the $X \to J/\psi\pi\pi$ decay [10] concluding that $J^{PC} = 1^{++}$ and 2^{-+} are the only assignments consistent with data. They also confirmed that the decay proceeds through a ρ intermediate state.

As far as the mass and width of the $X(3872)$ are concerned, BaBar has published an analysis of the $B \to XK$ decays with $X \to D^{*0}D^0$ [11] while Belle has updated the mass measurements in $X \to J/\psi\pi\pi$ decays [13]. The summary of all available mass measurements is shown in Fig. 2 where the measurements are separated by production and decay channel. There is an indication that the particle decaying into $J/\psi\pi\pi$ is different from the one decaying into $D^{*0}D^0$, their masses differing by about 4.5 standard deviations.

Recently, BaBar published an updated analysis of the $X(3872)$ with their complete dataset [14], studying the discovery mode of the $X(3872) \to J/\psi\pi^+\pi^-$. Updated branching fraction results (see Table II for details) and updated mesaurements of Δm (= $2.7 \pm 1.6 \pm 0.4$ Mev/c^2) and the natural width ($\Gamma < 3.3$ MeV/c^2) were provided. The central value for the $X(3872)$ natural width was found to be $\Gamma = (1.1 \pm 1.5 \pm 0.2)$MeV. All $X(3872)$ branching fractions measurements, in $J/\psi\pi\pi$ and $D^{*0}D^0$, are summarized in Tab. II.

3.2. The 1^{--} family

The easiest way to assign a value for J^{PC} to a particle, is to observe its production via e^+e^- annihilation, where the quantum numbers must be the same as the radiated photon: $J^{PC} = 1^{--}$. B factories can investigate a large range of masses for such particles by looking for events where the initial state radiation brings the e^+e^- center-of-mass energy down to the particle's mass (the so-called 'ISR' events). Alternatively, dedicated e^+e^- machines, like CESR and BEPC can scan directly the center-of-mass energies of interest.

The observation of new states in these processes started with the discovery of the $Y(4260) \to J/\psi\pi^+\pi^-$ by BaBar [15], promptly confirmed both in the same production process [16] and in direct production by CLEO-c [17]. The latter paper also reported evidence for $Y(4260) \to J/\psi\pi^0\pi^0$ and some events of $Y(4260) \to J/\psi K^+ K^-$.

While investigating whether the $Y(4260)$ decayed to $\psi(2S)\pi^+\pi^-$ BaBar did not find evidence for such a decay. Instead, they discovered a new 1^{--} state, the $Y(4350)$ [18]. While the absence of $Y(4260) \to \psi(2S)\pi^+\pi^-$ decays could be explained if the pion pair in the $J/\psi\pi^+\pi^-$ decay were produced with an
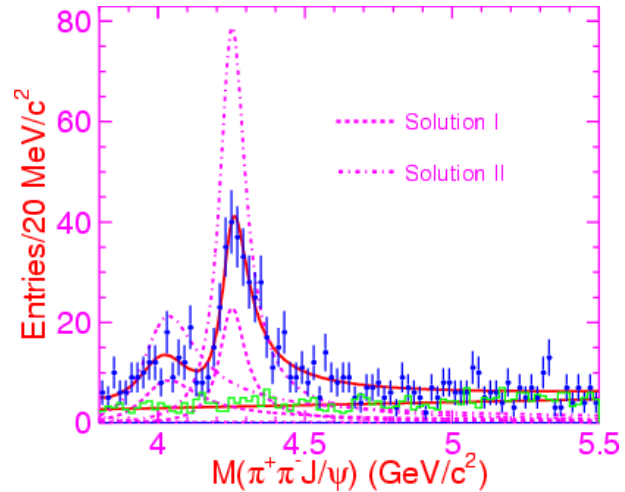

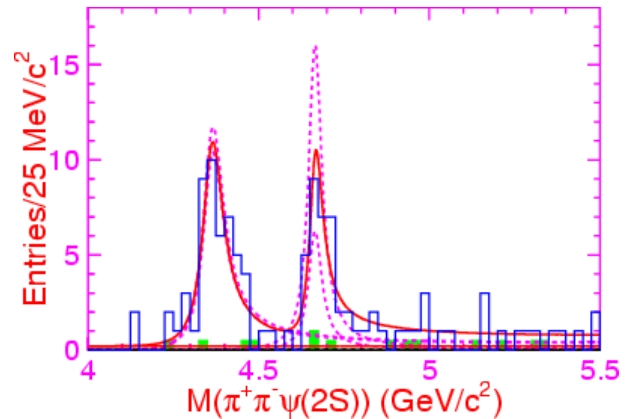Figure 3: $J/\psi\pi^+\pi^-$ *invariant mass in ISR production.*

Figure 4: $\psi(2S)\pi^+\pi^-$ *invariant mass in ISR production.*

intermediate state that is too massive to be produced with a $\psi(2S)$ (e.g. an f^0), the absence of $Y(4350) \to J/\psi\pi^+\pi^-$ is still to be understood, more statistics might be needed in case the $Y(4260)$ decay hides the $Y(4350)$.

Recently, Belle has published the confirmation of all of these 1^{--} states [19, 20]. Furthermore, they have unveiled a new state that was not clearly visible in the BaBar data due to the limited statistics: the $Y(4660)$. Figures 3 and 4 show the published invariant mass spectra for both the $J/\psi\pi^+\pi^-$ and the $\psi(2S)\pi^+\pi^-$ decays. A critical piece of information for unravelling the puzzle is whether the pion pair comes from a resonant state. Figure 5 shows the di-pion invariant mass spectra published by Belle for all the regions where new resonances have been observed. Although the subtraction of the continuum is missing, there is some indication that only the $Y(4660)$ has a well defined intermediate state (most likely an f_0), while others have a more complex structure.

A discriminant measurement between Charmonium

Table II Measured $X(3872)$ branching fractions, separated by production and decay mechanism. The ratio of the measurements in the two production mechanisms are also reported as $R_{0/+} = BF(B \to XK^-)/BF(B \to XK^0)$.

	BaBar	Belle
$\mathrm{BF}(B \to XK^-)\mathrm{BF}(X \to J/\psi\pi\pi)\times10^5$	$0.84\pm0.15 \pm 0.07$ [14]	1.05 ± 0.18 [7]
$\mathrm{BF}(B \to XK^0)\mathrm{BF}(X \to J/\psi\pi\pi)\times10^5$	$0.35\pm0.19 \pm 0.04$ [14]	0.99 ± 0.33
$\mathrm{BF}(B \to XK^-)\mathrm{BF}(X \to D^{*0}D^0)\times10^5$	$17 \pm 4 \pm 5$ [11]	$10.7\pm3.1^{+1.9}_{-3.3}$ [12]
$\mathrm{BF}(B \to XK^0)\mathrm{BF}(X \to D^{*0}D^0)\times10^5$	$22 \pm 10 \pm 4$ [11]	$17\pm7^{+3}_{-5}$ [12]
$R_{0/+}$ with $X \to J/\psi\pi\pi$	0.41 ± 0.25 [14]	0.94 ± 0.26
$R_{0/+}$ with $X \to D^{*0}D^0$	1.4 ± 0.6 [11]	–

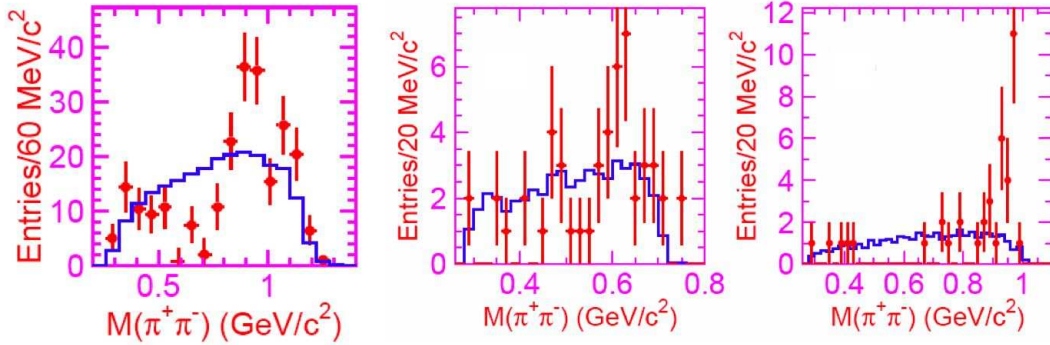Figure 5: *Di-pion invariant mass distribution in $Y(4260) \to J/\psi\pi^+\pi^-$ (left), $Y(4350) \to \psi(2S)\pi^+\pi^-$ (center), and $Y(4660) \to \psi(2S)\pi^+\pi^-$ (right) decays.*

states and new aggregation forms is the relative decay rate between these decays into Charmonium and the decays into two charm mesons. Searches have therefore been carried out for $Y \to D^{(*)}D^{(*)}$ decays [21–23] without any evidence for a signal. The most stringent limit is [23] $BF(Y(4260) \to D\bar{D})/BF(Y(4260) \to J/\psi\pi^+\pi^-) < 1.0@$ 90% confidence level.

3.3. The 3940 family

Three different states have been observed in recent years by the Belle collaboration with masses close to $3940\mathrm{Mev/c^2}$: one, named X, observed in continuum events (i.e. not in $Y(4S)$ decays) produced in tandem with a J/ψ meson and decaying into DD^* [24]; a second one, named Y, observed in B decays and decaying into $J/\psi\omega$ [25]; a third one, named Z produced in two-photon reactions and decaying into D-pairs [26]. While the X is consistent with both $J^{PC} = 0^{+-}$ and 1^{++}, the quantum number assignment of the Y and the Z states is clear: $J^{PC} = 1^{++}$ and 2^{++} respectively. Finally the Y is the only apparently broad state ($\Gamma = 87 \pm 34\mathrm{MeV}$).

Because of these quantum number assignments and their masses these states are good candidates for the radial excitation of the χ mesons, in particular the $Z(3940)$ meson could be identified with the $\chi_{c0}(2P)$ and the $Y(3940)$ with the $\chi_{c1}(2P)$. The unclear points are the identification of the $X(3940)$ state and the explanation of why the $Y(3940)$ state does not decay preferentially to D mesons.

The most recent development on this topic is the confirmation from the BaBar collaboration of the $Y(3940) \to J/\psi\omega$ decays [27]. The analysis utilizes the decay properties of the ω meson to extract a clean signal (see Fig. 6). The interesting part is that the mass and width measured in this paper are lower than when previously observed, albeit consistent ($m_Y = 3914.6^{+3.8}_{-3.4}(stat.) \pm 1.9(sys.)\mathrm{Mev/c^2}$, $\Gamma_Y = 33^{+12}_{-8}(stat.) \pm 5(sys.)\mathrm{MeV}$), opens the interesting possibility that the X and the Y particles be the same, thus solving the two aforementioned open issues.
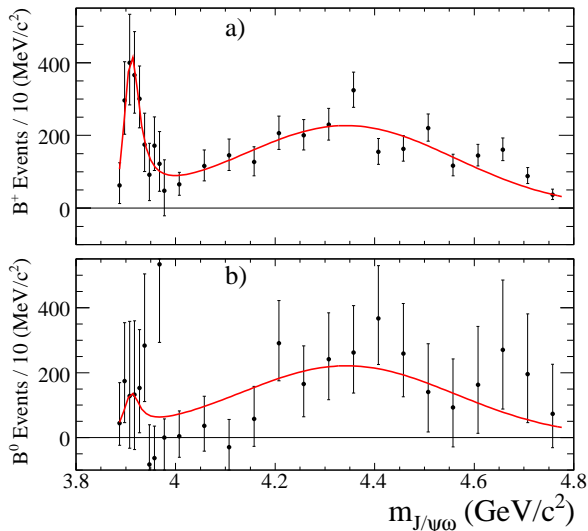
Figure 6: *The $J/\psi\omega$ distribution in a) $B \to J/\psi\omega K^+$ and b) $B \to J/\psi\omega K_S$ decays. The superimposed line is the result of the fit to the data.*

Figure 7: *The $\psi(2S)\pi$ invariant mass distribution in $B \to \psi(2S)\pi K$ decays.*

3.4. The $X(4160)$

As we have already discussed, it is critical to investigate decay channels of the new states into D meson pairs. Unfortunately the detection efficiency for D mesons is low, due to the large number of possible decay channels. The Belle collaboration has developed a partial reconstruction technique that overcomes this limitation in the case of new states produced in continuum paired with known Charmonium states [28]. The Charmonium is fully reconstructed, while only one of the two D mesons is reconstructed. The kinematics of the other is inferred from the known center-of-mass energy and the different possibile D mesons are discriminated on the basis of the missing mass.

This technique has allowed the confirmation of the $X(3940)$ production and decay, and, most interestingly, the observation of the $X(4160)$ state, decaying into DD^*. Given the fact that, for reasons yet to be understood, continuum events seem to produce $J^{PC} = 0^{-+}$ or 1^{++} states in pair with the J/ψ and since the measured mass is consistent with the expectations of a radial excitation of the η_c, this new state is likely to be an $\eta_c(3S)$.

3.5. The first charged state?: $Z(4430)$

Perhaps, the real turning point in the query for states beyond the Charmonium was the observation by the Belle Collaboration of a charged state decaying into $\psi(2S)\pi^{\pm}$ [29]. Figure 7 shows the fit to the $\psi(2S)\pi$ invariant mass distribution in $B \to \psi(2S)\pi K$ decays, returning a mass $M = 4433 \pm 4\text{MeV}/c^2$ and

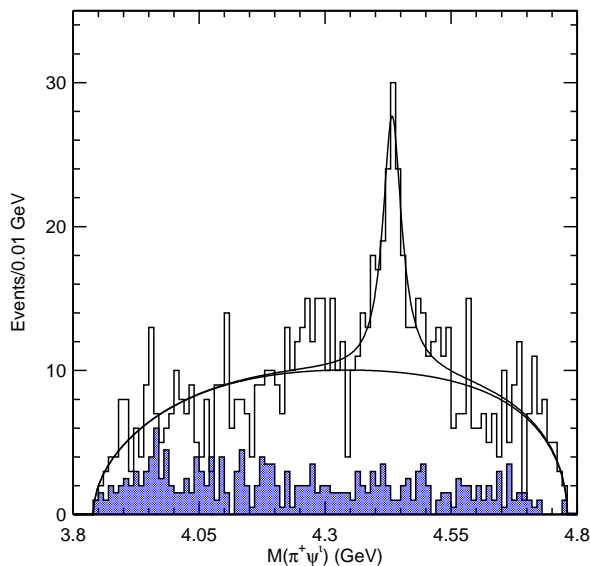a width $\Gamma = 44^{+17}_{-13}$ MeV. Due to the relevance of such an observation a large number of tests have been performed, breaking the sample in several subsamples and finding consistent results in all cases. Also, the possibility of a reflection of a $B \to \psi(2S)K^*$ decay has been falsified by explicitly vetoing windows in the $K\pi$ invariant mass.

In terms of quarks, such a state must contain a c and a $\bar{c}$, but given its charge it must also contain at least a u and a $\bar{d}$. The only open options are the tetraquark, the molecule or the threshold effects. The latter two options are possible due to the closeness of the $D_1 D^*$ threshold. Finding the corresponding neutral state, observing a decay mode of the same state or at least having a confirmation of its existence, are critical before a complete picture can be drawn.

4. Conclusions

More than 30 years after its first observation, the heavy-quarkonium is still an exciting laboratory for understanding QCD. The study of well established quarkonium states yields information on low energy QCD while the understanding of the quarkonium spectroscopy, predictable in potential models, allows searches for different aggregation states than the long established mesons.

The high statistics and quality data from B-Factories have produced a very large number of new states whose interpretation is still a matter of debate. This paper attempted a categorized review of the information pertaining to these states, as we know it today.

Many theoretical models have been developed to interpret the situation but the picture is far from complete: more precise predictions are needed from theory and a systematic experimental exploration of all possibile production and decay mechanisms of these new states is still in the works. It is clear that a Super-B Factory will be essential to gain a complete understanding of the true nature of these states.

5. Acknowledgments

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