Comment on the $X(3915)$ nonstandard hadron candidate

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Abstract. I review the experimental evidence for the $X(3915)$, the candidate nonstandard meson associated with $\omega J/\psi$ resonance-like peaks in $B \to K\omega J/\psi$ and $\gamma\gamma \to \omega J/\psi$ near $M(\omega J/\psi) = 3920$ MeV, and address the conjecture that it can be identified as the χ'_{c2}, the radial excitation of the χ_{c2} charmonium state. Since the partial decay width for $B \to KX(3915)$ is at least an order-of-magnitude higher than that for $B \to K\chi_{c2}$, its assignment as the χ'_{c2} is dubious.

1 Introduction

A number of meson candidates, dubbed the XYZ mesons, that contain charmed-quark anticharmed-quark ($c\bar{c}$) pairs but do not match expectations for any of the unassigned levels of the $[c\bar{c}]$ charmonium meson spectrum, have been observed in recent experiments [1]. In some cases, the distinction between the new states that are nonstandard hadrons and conventional charmonium mesons remains controversial.

This is especially the case for the $X(3915)$ that was first observed by Belle [2] and confirmed by BaBar [3, 4] as a near-threshold peak in the $\omega J/\psi$ invariant mass distribution in exclusive $B \to K\omega J/\psi$ decays (see Fig. 1a). An $\omega J/\psi$ mass peak with similar mass and width was seen in the two-photon fusion process $\gamma\gamma \to \omega J/\psi$, again by both Belle [5] and BaBar [6] (see Fig. 1b); BaBar reported its J^{PC} to be 0^{++}. The similar masses and widths of the peaks seen in the two production modes suggest that these are being produced a single state (i.e., the $X(3915)$). The Particle Data Group's (PDG) average values for the mass and width measurements from both production channels are [7]:

$$M(X(3915)) \quad = \quad 3918.4 \pm 1.9 \text{ MeV} \quad \text{and} \quad \Gamma(X(3915)) = 20.0 \pm 5.0 \text{ MeV}, \tag{1}$$

and the product branching fraction for $X(3915)$ production in B^+ meson decays is

$$\mathcal{B}(B^+ \to K^+X(3915)) \times \mathcal{B}(X \to \omega J/\psi) \quad = \quad 3.0 \pm 0.9 \times 10^{-5}. \tag{2}$$

The measured $\gamma\gamma \to \omega J/\psi$ production rates are used to extract the (J^{PC}-dependent) widths:

$$\Gamma_{\gamma\gamma}(X(3915)) \times \mathcal{B}(X \to \omega J/\psi) \quad = \quad 54 \pm 9 \text{ eV } (0^{++}) \text{ or } 11.4 \pm 2.7 \text{ eV } (2^{++}). \tag{3}$$

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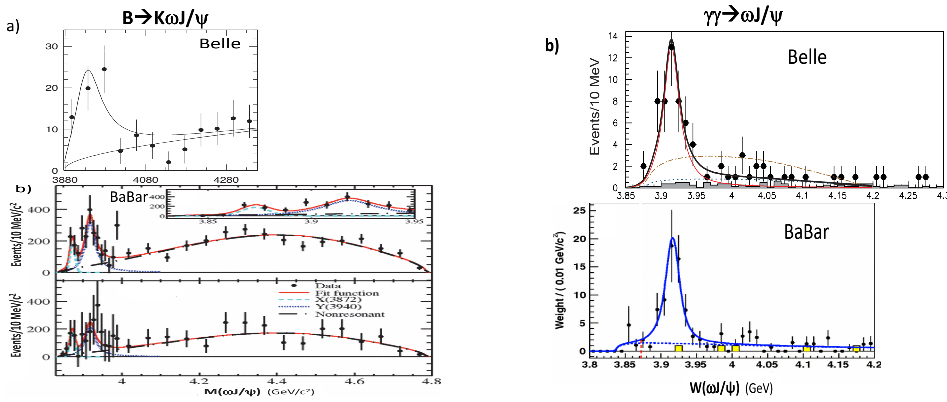

Figure 1. **a)** The $\omega J/\psi$ invariant mass spectrum for $B \to K\omega J/\psi$ decays from *(top)* Belle [2] and *(bottom)* Babar [4]. The low mass peak in the BaBar data is attributed to $X(3872) \to \omega J/\psi$ (see inset); the higher mass peak is the $X(3915) \to \omega J/\psi$ signal. The Belle analysis did not consider the possible presence of an $X(3872) \to \omega J/\psi$ signal. **b)** The $\omega J/\psi$ mass spectrum for $\gamma\gamma \to \omega J/\psi$ from *(top)* Belle [5] and *(bottom)* Babar [6].

2 The $X(3915)$ is not the χ'_{c0} charmonium state?

The Babar group's J^{PC} determination was based on an analysis of angular correlations amongst the final-state particles in their $\gamma\gamma \to \omega J/\psi$ event sample [6]. The important angles for distinguishing $J = 2^+$ from $J = 0^\pm$ are $\theta^*_{\rm n}$, the angle between $\vec{n}$, the normal to the $\omega \to \pi^+\pi^-\pi^0$ decay plane, and the $\gamma\gamma$ axis in the omega rest frame, and $\theta_{\rm ln}$, the angle between $\vec{n}$ and the direction of the ℓ^+ from $J/\psi \to \ell^+\ell^-$ decay (see Fig. 2a). Figure 2b shows the BaBar $\cos\theta^*_{\rm n}$ distribution together with the expectation for $J = 0^\pm$ as a solid red line and $J = 2^+$ as a dashed blue curve. There is a strong χ^2 penalty for the near-zero event likelihood near $\cos\theta^*_{\rm n} = \pm 1$ for the $J = 2^+$ hypothesis to fluctuate *upward* to the observed levels of ~ 8 and ~ 9 events, and this is the main support BaBar's $J = 0$ conclusion. The $J = 2$ hypothesis seems to fit the BaBar $\cos\theta_{\rm ln}$ distribution (see Fig. 2c) better than that for $J = 0$. But in this case, the likelihood of ~ 6 expected events near $\cos\theta_{\rm ln} = \pm 1$ to fluctuate *downward* to the observed $\simeq 2$ events is not so improbable. With $J = 0$ established, the 0^+ *vs.* 0^- discrimination mostly relies on the angle $\theta_{\rm n}$, which is the angle between the ω's flight path and $\vec{n}$ in the $\omega J/\psi$ restframe. The BaBar $\cos\theta_{\rm n}$ distribution shown in Fig. 2d favors 0^+ over 0^-, mostly because of the $\simeq 10$ events near $\cos\theta_{\rm n} = +1$, where the 0^- expectation is zero.

BaBar's $J^{PC} = 0^{++}$ assignment led them to suggest it as a suitable candidate for the 2^3P_0 charmonium state, commonly known as the χ'_{c0}, and it was listed as such in the 2014 PDG tables [8]. However, this assignment had some problems and was challenged for a number of reasons [9]: the partial width for $X(3915) \to \omega J/\psi$, which would be an OZI-suppressed decay mode for a charmonium state, was too large; the lack of evidence for $X(3915) \to D\bar{D}$, which would be the dominant mode for the χ'_{c0}; and the small, $\simeq 9$ MeV, mass splitting between the χ'_{c2} and the $X(3915)$, which is an order-of-magnitude lower than the smallest theoretical estimates for $M_{\chi'_{c2}} - M_{\chi'_{c0}}$ [10, 11]. This assignment was finally put to rest in 2017 by Belle, when they reported the observation of the $X^*(3860)$, a $D\bar{D}$ resonance with mass 3862^{+47}_{-35} MeV in $e^+e^- \to J/\psi D\bar{D}$ annhilations with preferred spin-parity of 0^{++} [12]. These properties, particularly the strong $D\bar{D}$ decay mode, match well the expectations for the χ'_{c0}, and the $X^*(3862)$ is clearly a much stronger candidate for this state than the $X(3915)$.

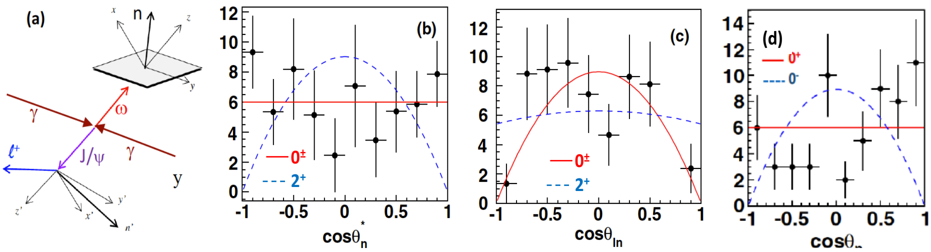

Figure 2. **a)** Directions used in the BaBar study of $\gamma\gamma \to \omega J/\psi$, where $\omega \to \pi^+\pi^-\pi^0$ and $J/\psi \to \ell^+\ell^-$. **b)** Comparison of the $\cos\theta^*_{\rm n}$ distribution with $J^P = 0^\pm$ (solid red) and 2^+ (dashed blue) expectations. **c)** The corresponding plot for $\cos\theta_{\rm ln}$. **d)** The $\cos\theta_{\rm n}$ distribution with expectations for 0^+ in solid red and 0^- in dashed blue. (From ref. [6].)

3 Is it the χ'_{c2} charmonium state?

The χ'_{c2} was first spotted by Belle [13] and subequently confirmed by BaBar [14] as a prominent $M(D\bar{D})$ peak in the two-photon fusion process $\gamma\gamma \to D\bar{D}$ that has a distinct $\sin^4\theta^*$ production angle dependence that is characteristic of a $J = 2$ state. The mass and width [7]:

$$M(\chi'_{c2}) \;=\; 3927.2 \pm 2.6\ \text{MeV} \quad \text{and} \quad \Gamma(\chi'_{c2}) = 24.0 \pm 6.0\ \text{MeV}, \tag{4}$$

are consistent with charmonium expectations for the χ'_{c2} and there are no reasons to question this assignment. The Belle (BaBar) $M(D\bar{D})$ and $dN/d|\cos\theta^*|$ distributions are shown in Fig. 3a (b). Belle and BaBar measurements of its two-photon production rate are also in good agreement and are characterized by the product

$$\Gamma_{\gamma\gamma}(\chi'_{c2}) \times \mathcal{B}(\chi'_{c2} \to D\bar{D}) \;=\; 210 \pm 40\ \text{eV}. \tag{5}$$

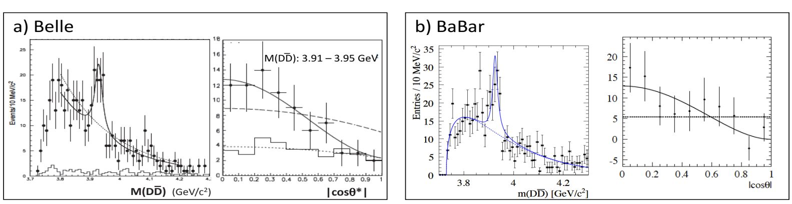

Figure 3. **a)** *left*: The $M(D\bar{D})$ distribution for $\gamma\gamma \to D\bar{D}$. The open histogram the D mass-sideband-determined background. The solid (dashed) curve shows results of a fit that includes (excludes) a χ'_{c2} signal. *right*: $dN/d|\cos\theta^*|$ for peak-region events with a solid (dashed) curve showing $J = 2$ ($J = 0$) expectations. The histogram is the non-resonant contribution. (From ref. [13].) **b)** Corresponding plots from BaBar [14].

BaBar's $J^{PC} = 0^{++}$ assignment for the $X(3915)$ was based on a comparison to a 2^{++} scenario that only considered a helicity-2 component (h_2) and ignored the possibility of any helicity-0 contribution. This assumption of "helicity-2 dominance" originate from a theoretical analysis that found that in two-photon production of tensor mesons, the helicity-0 component (h_0) is zero in the non-relativistic limit [15]. The authors of ref. [16] point out that in the case of charmonium, the suppression of helicity-0 contributions only applies to mesons that are 100% $c\bar{c}$, which is generally considered to be unlikely for charmonium mesons with masses above the $2m_D$ open-charm threshold (see, e.g., ref. [17]).

This is important because if the J^{PC} of the $X(3915)$ is 2^{++}, the mass peak identified with the $X(3915)$ could be conceivably be due to an $\omega J/\psi$ decay mode of the $\chi_{c2}(2P)$ charmonium state. The dashed lines in Fig. 4a show the ref. [16] comparison of the Belle $M(D\bar{D})$ and $|\cos\theta|$ with an $h_0 \simeq 1.5h_2$ mixture to represent the $X(3915)$. Figure 4b) shows BaBar's $\cos\theta^*_{\rm n}$ and $\cos\theta_{\rm ln}$ distributions with expectations for 0^{++}, and 2^{++} with $h = 0$ & $h = 2$. With the inclusion of some $h = 0$ contribution, the χ^2 distinction between 0^{++} and 2^{++} angular distributions is diminished and the authors conclude that the $X(3915)$ could be a χ'_{c2} state that contains a sizable non-$c\bar{c}$ component.

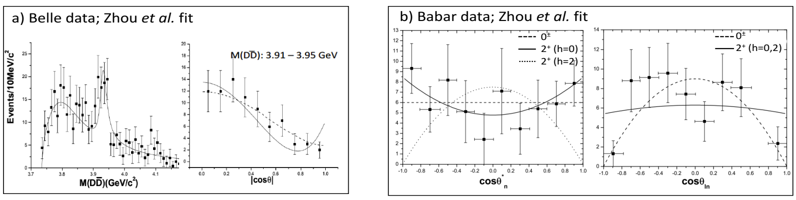

Figure 4. **a)** Belle $M(D\bar{D})$ (*left*) and $|\cos\theta^*|$ (*right*) distributions for $\gamma\gamma \to D\bar{D}$ production. The solid (dashed) curves show expectations for $h_0 = 0$ ($h_0 = 1.5h_2$). **b)** BaBar $\cos\theta^*_{\rm n}$ distribution (*left*) with a solid (dotted) curve showing expectations for 2^{++} with $h = 0$ ($h = 2$); the dashed curve is for 0^{++}. (*right*) The $\cos\theta_{\rm ln}$ distribution with a solid curve for 2^{++} with $h = 0$ or 2, and a dashed curve for 0^{++}. (From ref. [16].)

3.1 Other aspects of the $X(3915) = \chi'_{c2}$ assignment

In addition to violating helicity-2 dominance, which ref. [16] claims may not be a problem, there are other concerns with the $X(3915) = \chi'_{c2}$ assignment. These are briefly discussed here.

3.1.1 Mass and width differences

Belle and BaBar measurements of the $\gamma\gamma \to \omega J/\psi$ mass peak, 3915 ± 4 and 3919 ± 3 MeV, respectively, are both lower, by $\simeq 2\sigma$, than their respective $\chi'_{c2} \to D\bar{D}$ mass peak measurements, 3929 ± 5 and 3927 ± 3 MeV. Since the measurements reference well known masses – ω and J/ψ for the $X(3915)$ and D-meson for the χ'_{c2}– systematic effects are small.

On the other hand, a recent LHCb report on the $M(D\bar{D})$ distribution for inclusive D-meson pair production in high energy proton-proton collisions included observation of a distinct peak in the χ'_{c2} mass region, shown in Fig. 5a, with mass $M = 3921.9 \pm 0.6 \pm 0.2$ MeV, 2σ below the χ'_{c2} value listed in eqn. 4 [18]. The reported width, $\Gamma = 36.6 \pm 1.9 \pm 0.9$ MeV, is 2σ higher than the eqn. 4 value. The LHCb group attributes this peak to the χ'_{c2}.

Figure 5b shows recent BESIII $M(\omega J/\psi)$ results for $e^+e^- \to Y(4220) \to \gamma\omega J/\psi$, where there is a strong $X(3872) \to \omega J/\psi$ signal and 3σ "evidence" for two higher mass peaks [19]. The fitted mass of the middle peak is $M = 3926.4 \pm 2.5$ MeV, near the Belle and BaBar results for $\chi'_{c2} \to D\bar{D}$. Thus, the current situation with mass measurements is inconclusive.

3.1.2 A large OZI-violating $\omega J/\psi$ decay width for a $[c\bar{c}]$ meson

With the $\Gamma_{\gamma\gamma} \times \mathcal{B}$ values listed in eqns. 3 and 5, the χ'_{c2} assignment implies that

$$\frac{\mathcal{B}(\chi'_{c2} \to \omega J/\psi)}{\mathcal{B}(\chi'_{c2} \to D\bar{D})} = 0.05 \pm 0.02, \qquad (6)$$

which is large for an OZI-rule-violating decay of an above-open-charm-threshold charmonium state, and more than an order-of-magnitude higher than the measured corresponding

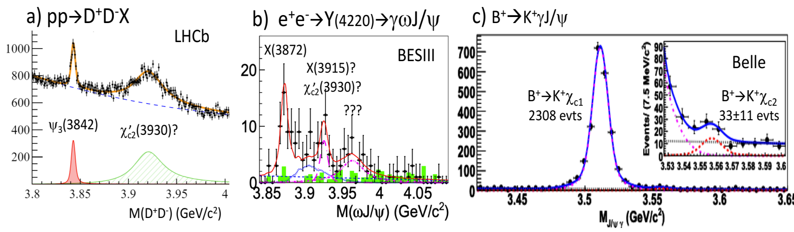

Figure 5. **a)** The $M(D^+D^-)$ distribution for inclusive D-meson pair production at the LHCb. The peak at 3842 MeV is the first observation of the ψ_3, the 1^3D_3 charmonium level. The broader peak near 3920 MeV is attributed by the LHCb group to the χ'_{c2} [18]. **b)** The $M(\omega J/\psi)$ distribution for $e^+e^- \to Y(4220) \to \omega J/\psi$ events from BESIII. An $X(3872) \to \omega J/\psi$ signal is evident. Additional peaks near 3925 MeV and 3960 MeV each have about 3σ significance [19]. **c)** $B^+ \to K^+\chi_{c1}$ and $K^+\chi_{c2}$ signals from the full Belle data set [20].

ratio for $\psi'' \to \pi^+\pi^- J/\psi$ and $D\bar{D}$. If $\chi'_{c2} \to D\bar{D}$ and $D\bar{D}^*$ are the dominant decay modes and $\Gamma_{\chi'_{c2}}(D\bar{D}^*) \approx \Gamma_{\chi'_{c2}}(D\bar{D})$ (as predicted in ref. [21]), then $\Gamma_{\chi'_{c2}}(\omega J/\psi) > 200$ keV (at the ~90% CL), and much larger than any measured OZI-violating width for a charmonium state.

3.1.3 $\mathcal{B}(B \to K\chi'_{c2}) >> \mathcal{B}(B \to K\chi_{c2})$?

In 2011, with their full event sample accumulated over ten years, Belle reported $\sim 3\sigma$ evidence for $B^+ \to K^+\chi_{c2}$ based on the 33 ± 11 event signal shown in Fig. 5c [20]. The inferred branching fraction, $\mathcal{B}(B^+ \to K^+\chi_{c2}) = 1.1 \pm 0.4 \times 10^{-5}$, is smaller that the *product* branching fraction for $X(3915) \to \omega J/\psi$ production in B^+ meson decays (eqn. 2). Since $\mathcal{B}(\chi'_{c2} \to D\bar{D})$ cannot exceed unity, eqn. 6 implies $\mathcal{B}(\chi'_{c2} \to \omega J/\psi) < 0.08$ (90% CL). Thus, if the $X(3915)$ produced in $B \to K\omega J/\psi$ is the χ'_{c2}, the B-meson decay width to $K^+\chi'_{c2}$ would be more than an order of magnitude larger than that to $K^+\chi_{c2}$. This contradicts theoretical expectations that $B \to K[c\bar{c}]$ decay widths decrease with increasing radial $[c\bar{c}]$ quantum numbers [22].

Suppression of $B \to K\chi^{(\prime)}_{c2}$ is not unexpected. The primary mechanism for B-meson ($\bar{b}q$) decays to $K[c\bar{c}]$ final states is $\bar{b} \to \bar{c}$ plus a virtual W^+ that, in turn, materializes as $c\bar{s}$. The final-state c- and $\bar{c}$-quark form the $[c\bar{c}]$ state and the $\bar{s}$- and "spectator" q-quark form the K. This process is only allowed for $J^{PC} = 0^{-+}, 1^{--}$ and 1^{++} $[c\bar{c}]$ states, decays to $[c\bar{c}]$ states with other J^{PC} values are higher-order and expected to be "factorization suppressed" [23]. The Belle results on $B \to K\chi_{c2}$ shown in Fig. 5c demonstrate that for $J^{PC} = 2^{++}$ $[c\bar{c}]$ states, factorization suppression is very effective: $\mathcal{B}(B \to K\chi_{c2}) < 0.04 \times \mathcal{B}(B \to K\chi_{c1})$ (90% CL).

4 Summary and conclusions

Despite its observation by different experiments in a variety of production channels, the nature of the $X(3915)$ remains a mystery. If it is a nonstandard XYZ meson, it cannot be easily interpreted by any of the proposed models for these states. For example: its mass is too low for a QCD-hybrid [24], and not near an appropriate threshold for a molecular state or a cusp effect [25]; the lack of evidence for a $\eta\eta_c$ decay mode [26] is problematic for a diquark-diantiquark assignmment [27]. Thus, if it is an XYZ meson, it is a very interesting one.

The sum total of existing data on $\omega J/\psi$ and $D\bar{D}$ production in the $\sim$ 3925 MeV mass region *cannot* be explained as being simply due to the χ'_{c2} charmonium state. While a (tenuous) case could be made that the near-3925 MeV mass peaks seen by the LHCb in $pp \to D\bar{D}X$, Belle and BaBar in $\gamma\gamma \to \omega J/\psi$ & $D\bar{D}$ and BESIII in $Y(4220) \to \gamma\omega J/\psi$ are all due to decays of the χ'_{c2}, the existing evidence is not conclusive. Moreover, a very strong case can be made *against* a χ'_{c2} interpretation of the $\omega J/\psi$ peak seen in $B \to K\omega J/\psi$ decays.

More refined mass and width measurements are needed, and reliable, separate J^{PC} determinations for the $\omega J/\psi$ peaks produced via $\gamma\gamma$ fusion, radiative $Y(4220)$ transitions, and B-meson decays that eschew the helicity-2 dominance constraint are essential. The LHCb group has demonstrated that they can isolate clean $B^+ \to K^+\omega J/\psi$ signals with good efficiency [28] and I look forward to high-statistics results from them in the near future.

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