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

Stephen Lars Olsen$^{1,*}$

$^1$University of Chinese Academy of Science, Beijing 100049, CHINA

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 $\chi_{c2}'$, the radial excitation of the $\chi_{c2}$ 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 $\chi_{c2}'$ 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]:

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

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

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

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

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

*e-mail: solsenha@gmail.com
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 $J = 0^+$ are $\theta_0^*$, 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 $\theta_n$, the angle between $\vec{n}$ and the direction of the $\ell^+ \ell^-$ from $J/\psi \to \ell^+\ell^-$ decay (see Fig. 2a). Figure 2b shows the BaBar $\cos \theta_0^*$ distribution together with the expectation for $J = 0^+$ as a solid red line and $J = 2^+$ as a dashed blue curve. There is a strong $\chi^2$ penalty for the near-zero event likelihood near $\cos \theta_0^* = \pm 1$ for the $J = 2^+$ hypothesis to fluctuate upward to the observed levels of $\sim 8$ and $\sim 9$ events, and this is the main support BaBar’s $J = 0$ conclusion. The $J = 2$ hypothesis seems to fit the BaBar $\cos \theta_0^*$ distribution (see Fig. 2b) better than that for $J = 0$. But in this case, the likelihood of $\sim 6$ expected events near $\cos \theta_0^* = \pm 1$ to fluctuate downward to the observed $\sim 2$ events is not so improbable. With $J = 0$ established, the $0^+$ vs. $0^-$ discrimination mostly relies on the angle $\theta_n$, which is the angle between the $\omega$’s flight path and $\vec{n}$ in the $\omega J/\psi$ restframe. The BaBar $\cos \theta_n$ distribution shown in Fig. 2c favors $0^+$ over $0^-$, mostly because of the $\sim 10$ events near $\cos \theta_n = +1$, 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 $\chi'_{c0}$, 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 $\chi'_{c0}$; and the small, $\sim 9$ MeV, mass splitting between the $\chi'_{c2}$ 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 $3862^{+42}_{-35}$ MeV in $e^+e^- \to J/\psi D\bar{D}$ annihilations with preferred spin-parity of $0^{++}$ [12]. These properties, particularly the strong $D\bar{D}$ decay mode, match well the expectations for the $\chi'_{c0}$, and the $X''(3862)$ is clearly a much stronger candidate for this state than the $X(3915)$.
3 Is it the $\chi'_{c2}$ charmonium state?

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

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

are consistent with charmonium expectations for the $\chi'_{c2}$ 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

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

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 \cite{15}. The authors of ref. \cite{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. \cite{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. 4 show the ref. [16] comparison of the Belle $M(D\bar{D})$ and $|\cos \theta|$ with an $h_0 \approx 1.5h_2$ mixture to represent the $X(3915)$. Figure 3b) shows BaBar’s $\theta_{h_0}$ and $\cos \theta_{h_0}$ distributions with expectations for $0^{++}$, and $2^{++}$ with $h = 0$ & $h = 2$. With the inclusion of some $h = 0$ contribution, the $\chi^2$ distinction between $0^{++}$ and $2^{++}$ angular distributions is diminished and the authors conclude that the $X(3915)$ could be a $\chi'_{c2}$ 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 $\gamma\gamma \rightarrow D\bar{D}$ production. The solid (dashed) curves show expectations for $h_0 = 0$ ($h_0 = 1.5h_2$). b) BaBar $\cos \theta_{h_0}$ distribution (left) with a solid (dotted) curve showing expectations for $2^{++}$ with $h = 0$ ($h = 2$); the dashed curve is for $0^{++}$ (right). The $\cos \theta_{h_0}$ 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 $\gamma\gamma \rightarrow \omega J/\psi$ mass peak, $3915 \pm 4$ and $3919 \pm 3$ MeV, respectively, are both lower, by $\approx 2\sigma$, than their respective $\chi'_{c2} \rightarrow D\bar{D}$ mass peak measurements, $3929 \pm 5$ and $3927 \pm 3$ MeV. Since the measurements reference well known masses – $\omega$ and $J/\psi$ for the $X(3915)$ and $D$-meson for the $\chi'_{c2}$ – 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 $\chi'_{c2}$ mass region, shown in Fig. 5, with mass $M = 3921.9 \pm 0.6 \pm 0.2$ MeV, $2\sigma$ below the $\chi'_{c2}$ value listed in eqn. [18]. The reported width, $\Gamma = 36.6 \pm 1.9 \pm 0.9$ MeV, is $2\sigma$ higher than the eqn. [18] value. The LHCb group attributes this peak to the $\chi'_{c2}$.

Figure 5b shows recent BESIII $M(\omega J/\psi)$ results for $e^+e^- \rightarrow Y(4220) \rightarrow \gamma\omega J/\psi$, where there is a strong $X(3872) \rightarrow \omega J/\psi$ signal and $3\sigma$ “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 $\chi'_{c2} \rightarrow D\bar{D}$. 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 $\Gamma_{\gamma\gamma} \times B$ values listed in eqns. [3] and [5] the $\chi'_{c2}$ assignment implies that

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

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
ratio for $\psi'' \rightarrow \pi^+\pi^- J/\psi$ and $D\bar{D}$. If $\chi''_{c2} \rightarrow D\bar{D}$ 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 $\mathcal{B}(B \rightarrow K\chi'_{c2}) >> \mathcal{B}(B \rightarrow K\chi''_{c2})$?

In 2011, with their full event sample accumulated over ten years, Belle reported ~ 3σ evidence for $B^+ \rightarrow K^+\chi'_{c2}$ based on the $33 \pm 11$ event signal shown in Fig. 5. The inferred branching fraction, $\mathcal{B}(B^+ \rightarrow K^+\chi'_{c2}) = 1.1 \pm 0.4 \times 10^{-5}$, is smaller than the product branching fraction for $X(3915) \rightarrow \omega J/\psi$ production in $B^+$ meson decays (eqn. 2). Since $\mathcal{B}(\chi''_{c2} \rightarrow D\bar{D})$ cannot exceed unity, eqn. [4] implies $\mathcal{B}(\chi''_{c2} \rightarrow \omega J/\psi) < 0.08$ (90% CL). Thus, if the $X(3915)$ produced in $B \rightarrow K\omega J/\psi$ is the $\chi''_{c2}$, 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 $B \rightarrow K[\bar{c}c]$ decay widths decrease with increasing radial [\bar{c}c] quantum numbers [22].

3.1.4 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 $\eta_{c2}$ decay mode [26] is problematic for a diquark-diantiquark assignment [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 ~3925 MeV mass region cannot be explained as being simply due to the $\chi''_{c2}$ charmonium state. While a (tenuous) case could be made that the near-3925 MeV mass peaks seen by the LHCb in $pp \rightarrow D\bar{D}X$, Belle and BaBar in $\gamma\gamma \rightarrow \omega J/\psi$ & $D\bar{D}$ and BESIII in $Y(4220) \rightarrow \gamma\omega J/\psi$ are all due to decays of the $\chi''_{c2}$, the existing evidence is not conclusive. Moreover, a very strong case can be made against a $\chi''_{c2}$ interpretation of the $\omega J/\psi$ peak seen in $B \rightarrow K\omega J/\psi$ 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 $B^+ \rightarrow K^+ \omega J/\psi$ signals with good efficiency [28] and I look forward to high-statistics results from them in the near future.

5 Acknowledgements

I congratulate Phi-to-Psi-2018 organizers for an interesting and provocative meeting. This work is supported by the CAS President’s International Fellowship Initiative.

References

[1] S.L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90, 015003 (2018), 1708.04012
[2] K. Abe et al. (Belle), Phys. Rev. Lett. 94, 182002 (2005), hep-ex/0408126
[3] B. Aubert et al. (BaBar), Phys. Rev. Lett. 101, 082001 (2008), 0711.2047
[4] P. del Amo Sanchez et al. (BaBar), Phys. Rev. D82, 011101 (2010), 1005.5190
[5] S. Uehara et al. (Belle), Phys. Rev. Lett. 104, 092001 (2010), 0912.4451
[6] J.P. Lees et al. (BaBar), Phys. Rev. D86, 072002 (2012), 1207.2651
[7] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98, 030001 (2018)
[8] K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)
[9] F.K. Guo, U.G. Meissner, Phys. Rev. D86, 091501 (2012), 1208.1134
[10] H. Wang, Y. Yang, J. Ping, Eur. Phys. J. A50, 76 (2014)
[11] S.L. Olsen, Phys. Rev. D91, 057501 (2015), 1410.6534
[12] K. Chilikin et al. (Belle), Phys. Rev. D95, 112003 (2017), 1704.01872
[13] S. Uehara et al. (Belle), Phys. Rev. Lett. 96, 082003 (2006), hep-ex/0512035
[14] B. Aubert et al. (BaBar), Phys. Rev. D81, 092003 (2010), 1002.0281
[15] M. Krammer, H. Krasemann, Phys. Lett. 73B, 58 (1978)
[16] Z.Y. Zhou, Z. Xiao, H.Q. Zhou, Phys. Rev. Lett. 115, 022001 (2015), 1501.00879
[17] M.R. Pennington, D.J. Wilson, Phys. Rev. D76, 077502 (2007), 0704.3384
[18] R. Aaij et al. (LHCb) (2019), 1903.12240
[19] M. Ablikim et al. (BESIII) (2019), 1903.04695
[20] V. Bhardwaj et al. (Belle), Phys. Rev. Lett. 107, 091803 (2011), 1005.0177
[21] T. Barnes, S. Godfrey, E.S. Swanson, Phys. Rev. D72, 054026 (2005), hep-ph/0505002
[22] G.T. Bodwin et al., Phys. Rev. D46, R3703 (1992), hep-ph/9208254
[23] M. Beneke et al., Phys. Rev. Lett. 83, 1914 (1999), hep-ph/9905312
[24] L. Liu et al. (Hadron Spectrum), JHEP 07, 126 (2012), 1204.5425
[25] S.L. Olsen, EPJ Web Conf. 202, 01003 (2019), 1812.10947
[26] A. Vinokurova et al. (Belle), JHEP 06, 132 (2015), [Erratum: JHEP02,088(2017)], 1501.06351
[27] R.F. Lebed, A.D. Polosa, Phys. Rev. D93, 094024 (2016), 1602.08421
[28] G. Andreassi, Ph.D. thesis, University of Rome, Sapienza (2014)