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Two topics on charmonium-like states *

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Abstract

Two topics about the charmonium-like spectrum are discussed here. In the first part, we present that in a combined analysis of $\gamma\gamma \to D\bar{D}, J/\psi\omega$ processes the $X(3915)$ is preferred to be the same tensor state as the $X(3930)$ by the experiment data. In the second part, we show that, in a coupled-channel unitarized model, the mass distribution data sets of $X(4260) \to J/\psi\pi^+\pi^-, (DD^*)^\pm\pi^\mp, (D^*D^*)^\pm\pi^\mp$ could be described perfectly at the same time. By analyzing the singularity structure of the amplitudes, one could find that the peak of $Z_c(3900)$ line-shape is mainly contributed by a thirdsheet pole at about 3.875 ± 0.016GeV. The analysis clearly demonstrates that a good quantitative description of the mass distribution data requires the pole contribution to the $Z_c(3900)$ line-shape rather than the pure cusp effect.

Keywords: Charmonium-like spectroscopy, coupled-channel unitarity, hadronic molecule

1. Introduction

More and more "XYZ" states have been observed in recent years, which greatly expand the charmonium-like and bottomonium-like families and also introduce more problems into the study of heavy quarkonium spectroscopy. The conventional understanding of the usual quarkonium states is to regard them as bound states of quarks-anti-quark pairs in some phenomenological potentials such as a sum of the one-gluon-exchange Coulomb-type potential, the spin-independent linear confinement potential, and some other potentials to produce the hyperfine structures in non-relativistic potential models. These kinds of quark potential models, which used to be successful in predicting the mass spectroscopy of the charmonium states below the $D\bar{D}$ threshold, usually fail to describe these newly-observed states, whose masses are usually much lower than the predicted values. The largest discrepancy could be more than one hundred MeV. These discrepancies cause theorists to pay more attention to the coupled-channel effects or some other mechanisms in similar spirits. Another puzzling fact is that many charged exotic line-shape signals, dubbed Z_c's or Z_b's, have been observed by experimental groups [1]. If these structures are really produced by resonant states, they can not be accommodated in the conventional quark models, but contain at least four quark components in exotic forms of matter such as hadronic molecules, quark-gluon hybrids, tetraquarks [2]. These phenomena imply that there are more unknown properties for the hadronic states with heavy quarks and further attention should be paid on these topics.

In this paper, we are devoted to discuss two topics in this region. In the first part, the quantum numbers of the $X(3915)$ are re-analyzed. In the second part, we present a coupled-channel method to understand the natures of the newly-observed Z_c states. Conclusions are made in the last section.

2. The quantum numbers of $X(3915)$

Among these "XYZ" states, the $X(3915)$ was reported by Belle as a narrow resonance in the two-photon fusion

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process $\gamma\gamma \to J/\psi\omega$ [3], in which both assignments of $J^{PC} = 0^{++}$ and 2^{++} are acceptable. Then, this state was suggested to be the $\chi_{c0}(2P)$ state in Ref. [4] based on the analyses of their decay widthes in the Quark-Pair-Creation model. *BABAR* confirmed the existence of the $X(3915)$ and also suggested that its J^{PC} is 0^{++} by studying the angular distributions among the final leptons and pions of J/ψ and ω [5]. In the PDG Table [1], this state is quoted as $\chi_{c0}(2P)$ now. However, there are several questions if $X(3915)$ is assigned to $\chi_{c0}(2P)$. First, as a scalar charmonium state, the expected dominant decay mode of $\chi_{c0}(2P)$ is the Okubo-Zweig-Iizuka allowed $D\bar{D}$ mode, but in $\gamma\gamma \to D\bar{D}$ mass distribution there is only the signal of a tensor $X(3930)$. Secondly, the mass splitting of $X(3915)$ and $X(3930)$ is much smaller than the calculated value in the quark potential model and also much smaller than the mass splitting of $\chi_{b0}(2P)$ and $\chi_{b2}(2P)$, which are well established [6]. Furthermore, Olsen argued that this assignment implies a confliction between the branching fractions $\mathcal{B}(\chi_{c0}(2P) \to J/\psi\omega)$ obtained from $\gamma\gamma \to J/\psi\omega$ and $B \to K\,X(3915)$.

By a closer examination of *BABAR*'s analysis against the assignment of 2^{++} to $X(3915)$, one finds that the argument is based on the helicity-2 dominance assumption which originally comes from the quark model calculations on the decay of a quarkonium to two massless vector particles [7, 8]. As for the states containing more than two quarks, whether this assumption is still reasonable is not proven in the literature. The masses of the states much higher than the $D\bar{D}$ threshold are better understood in hadron-loop mechanisms, in which these states might contain sizable non-$q\bar{q}$ components. So, the helicity-2-dominance assumption is not assured to be indispensable. At present stage, whether the helicity-2 contribution is dominant or not for charmonium-like states should be determined by the experiment.

The helicity-2-dominance assumption is also used by Belle and *BABAR* in their determinations of the quantum numbers of $X(3930)$ in the $\gamma\gamma \to D\bar{D}$ process, and these analyses have also been regarded as the verification of the assumption by *BABAR*. We can first check whether this assumption is necessary in analyzing the data of $\gamma\gamma \to D\bar{D}$ process in determining the properties of $X(3930)$.

The differential cross section of $\gamma\gamma \to D\bar{D}$ could be represented by two independent helicity amplitudes $\mathcal{M}_{+\pm}$ as

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2\rho(s)s}(|\mathcal{M}_{++}|^2 + |\mathcal{M}_{+-}|^2), \qquad (1)$$

where $\rho(s) = \sqrt{(s - 4m_D^2)/s}$. The partial wave expansions of $\mathcal{M}_{+\pm}$ are [9]

$$\mathcal{M}_{++}(s,\cos\theta) = 16\pi\sum_{J\geq 0}(2J+1)F_{J0}(s)d^J_{0,0}(\cos\theta),$$
$$\mathcal{M}_{+-}(s,\cos\theta) = 16\pi\sum_{J\geq 2}(2J+1)F_{J2}(s)d^J_{2,0}(\cos\theta), \qquad (2)$$

in which $F_{J,0}$ and $F_{J,2}$ are the partial wave amplitudes for helicity-0 and helicity-2 with vanishing odd-J partial waves. The d functions are Wigner d-functions. We assume that the lowest two partial waves, the S-wave and D-wave, are contributed by a 0^{++} resonance and a 2^{++} one, respectively, dominating the $\gamma\gamma \to D\bar{D}$ process below 4.2GeV. The 0^{++} resonance contributes only to the helicity-0 amplitude through S wave, while the 2^{++} resonance contributes to both helicity-0 and helicity-2 amplitudes. For simplicity, we parameterize every $\alpha_{i,J\lambda}(s)$ function by one constant parameter instead of by non-singular polynomials with more free parameters, and for the lack of information about $D\bar{D} \to J/\psi\omega$ scattering amplitude, the relative strength and phase between the S-wave and the D-wave of helicity-0 amplitude are parametrized by a complex number as $\beta e^{i\phi}$.

Thus, the helicity amplitudes of $\gamma\gamma \to D\bar{D}$ are represented phenomenologically as

$$\begin{aligned}\mathcal{M}_{++} &= 16\pi(\mathcal{A}_0(s) + \beta_1 e^{i\phi_1}\mathcal{A}_2(s)\times 5\times d^2_{0,0}(\cos\theta)),\\ \mathcal{M}_{+-} &= 16\pi(\beta_2 e^{i\phi_2}\mathcal{B}_2(s)\times 5\times d^2_{2,0}(\cos\theta)),\end{aligned} \qquad (3)$$

where $\mathcal{A}_0(s) = \frac{M_{\chi_{c0'}}\Gamma_{\chi_{c0'}}(s)}{M^2_{\chi_{c0'}} - s - iM_{\chi_{c0'}}\Gamma_{\chi_{c0'}}(s)}$, $\mathcal{A}_2(s) = \mathcal{B}_2(s) = \frac{M_{\chi_{c2'}}\Gamma_{\chi_{c2'}}(s)}{M^2_{\chi_{c2'}} - s - iM_{\chi_{c2'}}\Gamma_{\chi_{c2'}}(s)}$. One could use these amplitudes to fit the $\gamma\gamma \to D\bar{D}$ mass distributions and the angular distribution simultaneously. The parameters are $M_{\chi_{c0'}}$, $\Gamma_{\chi_{c0'}}$, $M_{\chi_{c2'}}$, $\Gamma_{\chi_{c2'}}$, β_1, ϕ_1, and β_2.

The mass distribution and angular distribution data are well reproduced when all parameters are set free, but the β_1 and β_2 have sizable uncertainties. Even if β_2 is fixed at about 0.5, which means a dominant helicity-0 amplitude, the fit qualities are also similar to the all-free fit. The numerical results mean that the analyses of $\gamma\gamma \to D\bar{D}$ data do not verify the helicity-2-dominance assumption and the experimental analyses might be over-restricted.

Since the masses and widthes of the $X(3915)$ and $X(3930)$ are almost degenerate, we assume that they might correspond to the same state coupling to different channels, and then check whether this assumption could describe the observed data without the assumption of helicity-2-dominance.

The ratios $\mathcal{R} = \beta_1/\beta_2$ of the 2^{++} intermediate state in $\gamma\gamma \to J/\psi\omega, D\bar{D}$ are the same according to the pole dominance assumption. We then perform another fit,