SEARCH FOR VECTOR CHARMONIUM(-LIKE) STATES IN $e^+e^- \to \omega\chi_{cJ}$*

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The cross sections of $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ have been measured by BESIII. We try to search for vector charmonium(-like) states $Y(4220)$, $Y(4360)$, $\psi(4415)$ and $Y(4660)$ in the $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ line shapes. The $\omega\chi_{c0}$ mainly comes from $Y(4220)$, $\omega\chi_{c1}$ mainly comes from $Y(4660)$ and $\omega\chi_{c2}$ mainly comes from $\psi(4415)$, maybe partly comes from $Y(4360)$ or $Y(4660)$. For the charmonium(-like) states that are not significant in the $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ line shape, we also give the 90% confidence level upper limits on the electron partial width multiplied by branching fraction. These results are helpful to study the nature of charmonium(-like) states in this energy region.

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In recent years, charmonium physics has gained renewed strong interest from both the theoretical and the experimental side due to the observation of charmonium-like states, such as $X(3872)$ [1, 2], $Y(4260)$ [3–5], $Y(4360)$ [6, 7] and $Y(4660)$ [7]. These states do not fit in the conventional charmonium spectroscopy and could be exotic states that lie outside the quark model [8]. The 1^{--} Y-states are all observed in $\pi^+\pi^-J/\psi$ or $\pi^+\pi^-\psi(3686)$, while recently, one state (called $Y(4220)$) is observed in $e^+e^- \to \omega\chi_{c0}$ [9, 10], and two states (called $Y(4220)$ and $Y(4390)$) are observed in $e^+e^- \to \pi^+\pi^-h_c$ [11]. It indicates that the Y-states also can be searched for by other charmonium transition decays. On the other hand, there are still some charmonium states predicted by the potential models which have not yet been observed experimentally, especially in the mass region higher than 4 GeV/c^2. The study of these 1^{--} Y-states is very helpful

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to clarify the missing predicted charmonium states in a potential model. In all Y-states, maybe some are conventional charmonium. So it is important to confirm which Y-states are charmonium and which are exotic states.

In all decay channels, the cross sections for $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ are relatively large, so we can search for Y-states in $\omega\chi_{cJ(J=0,1,2)}$ line shape. The authors of Ref. [9] perform a first search for the decay $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$. The process $e^+e^- \to \omega\chi_{c0}$ is observed around the center-of-mass energy $\sqrt{s} = 4.23$ and 4.26 GeV, while there are no significant $\omega\chi_{c1}$ and $\omega\chi_{c2}$ signals. Reference [10] also performs a search for $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ using the data from $\sqrt{s} = 4.42$ to 4.6 GeV. The decay $e^+e^- \to \omega\chi_{c1}$ is observed around $\sqrt{s} = 4.6$ GeV and decay $e^+e^- \to \omega\chi_{c2}$ is observed around $\sqrt{s} = 4.42$ GeV. The processes $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ are all observed while the line shapes are different. Figure 1 shows the cross sections for $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ from BESIII for the center-of-mass energy from $\sqrt{s} = 4.2$ to 4.6 GeV. The different line shapes observed for $\omega\chi_{cJ(J=0,1,2)}$ might indicate that the production mechanisms are different, and that nearby resonances have different branching fractions to the $\omega\chi_{cJ(J=0,1,2)}$ decay modes.

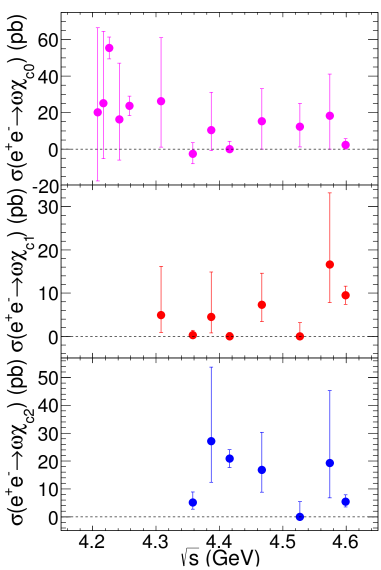

Fig. 1. Cross sections of $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ from BESIII. The top plot is for $e^+e^- \to \omega\chi_{c0}$, the middle plot is for $e^+e^- \to \omega\chi_{c1}$, and the bottom plot is for $e^+e^- \to \omega\chi_{c2}$.

Many theoretical papers have talked about the processes $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ [12–16], so it is important to get the coupling strength between $\omega\chi_{cJ(J=0,1,2)}$ and different charmonium(-like) states; it can be helpful to develop the theoretical models. Above 4.2 GeV, the all observed vector charmonium(-like) states are $Y(4220)$, $Y(4360)$, $\psi(4415)$ and $Y(4660)$. In this paper, we try to search for these vector charmonium(-like) states in the $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ line shape. The $Y(4220)$ is above $\omega\chi_{c0}$ threshold, and the $Y(4360)$, $\psi(4415)$ and $Y(4660)$ are all above $\omega\chi_{c2}$ threshold.

From Fig. 1, we can see that there is an obvious structure around 4.23 GeV in the line shape of $e^+e^- \to \omega\chi_{c0}$. Assuming that the $\omega\chi_{c0}$ signals come from a single resonance, we fit the cross section with a phase-space modified Breit–Wigner (BW) function; that is,

$$\sigma(\sqrt{s}\,) = \left|\mathrm{BW}(\sqrt{s}\,)\sqrt{\frac{\mathrm{PS}(\sqrt{s}\,)}{\mathrm{PS}(M)}}\right|^2 , \tag{1}$$

where $\mathrm{PS}(\sqrt{s}\,)$ is the 2-body phase-space factor,

$$\mathrm{BW}(\sqrt{s}\,) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}(\omega\chi_{c0})\Gamma_{\mathrm{tot}}}}{s - M^2 + iM\Gamma_{\mathrm{tot}}}$$

is the BW function for a vector state, with mass M, total width Γ_{tot}, electron partial width Γ_{ee}, and the branching fraction to $\omega\chi_{c0}$, $\mathcal{B}(\omega\chi_{c0})$. From the fit, we can only extract $\Gamma_{ee}\mathcal{B}(\omega\chi_{c0})$.

Figure 2 shows the fit result. The fit results for the structure $Y(4220)$ are $M = (4226\pm8)$ MeV/c^2, $\Gamma = (39\pm12)$ MeV, and $\Gamma_{ee}\mathcal{B}(\omega\chi_{c0}) = (2.8\pm0.5)$ eV. The goodness of the fit is $\chi^2/\mathrm{n.d.f.} = 6.5/10$, corresponding to a confidence level of 77%. The mass and width are consistent with the state $Y(4220)$ found in $e^+e^- \to \pi^+\pi^-h_c$ [11] and $\pi^+\pi^-J/\psi$ [17]. The cross sections for $e^+e^- \to \omega\chi_{c0}$ around $\sqrt{s} = 4.36, 4.42$ and 4.6 GeV is close to 0, so the contributions from states $Y(4360)$, $\psi(4415)$ and $Y(4660)$ are small, we set 90% confidence level (C.L.) upper limits for them.

Assuming that $\omega\chi_{c0}$ comes from two resonances $Y(4220)$ and $Y(4360)$, we fit the cross section with coherent sum of two constant width relativistic BW functions; that is,

$$\sigma(\sqrt{s}\,) = \left|\mathrm{BW}_1(\sqrt{s}\,)\sqrt{\frac{\mathrm{PS}(\sqrt{s}\,)}{\mathrm{PS}(M_1)}} + \mathrm{BW}_2(\sqrt{s}\,)\sqrt{\frac{\mathrm{PS}(\sqrt{s}\,)}{\mathrm{PS}(M_2)}}e^{i\phi_1}\right|^2 , \tag{2}$$

where ϕ_1 is relative phase, BW_1s mass and width are fixed at the fit results for $Y(4220)$, and BW_2s mass and width are fixed at the world average values [18] for $Y(4360)$. We use a least χ^2 method to fit the cross section. The likelihood value can be got using the formula

$$\mathcal{L} = e^{-\frac{1}{2}\chi^2} . \tag{3}$$

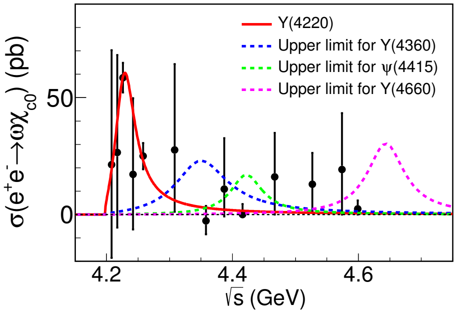

Fig. 2. (Color online) Fit to the cross section of $e^+e^- \to \omega\chi_{c0}$ from BESIII. The solid red curve shows the fit result using $Y(4220)$ structure, the dashed black (blue) one is the 90% C.L. upper limit for $Y(4360)$, the dashed light gray (green) one is the 90% C.L. upper limit for $\psi(4415)$, and the dashed gray (purple) one is the 90% C.L. upper limit for $Y(4660)$.

We will calculate the 90% C.L. upper limit on the electron partial width multiplied by branching fraction $\Gamma_{ee}^{Y(4360)}\mathcal{B}(Y(4360) \to \omega\chi_{c0})$ $(\Gamma\mathcal{B})$ for $Y(4360)$. The upper limit is determined by finding the value $(\Gamma\mathcal{B})^{\rm up}$ such that $\int_0^{(\Gamma\mathcal{B})^{\rm up}} {\rm d}(\Gamma\mathcal{B})/\int_0^\infty {\rm d}(\Gamma\mathcal{B}) = 0.90$, where $\mathcal{L}$ is the value of the likelihood as a function of $\Gamma\mathcal{B}$. From the fit result, the 90% C.L. upper limit for $Y(4360)$ is $\Gamma_{ee}^{Y(4360)}\mathcal{B}(Y(4360) \to \omega\chi_{c0}) < 3.0$ eV.

Using the same method, we also assume that $\omega\chi_{c0}$ comes from $Y(4220)$ and $\psi(4415)$, the upper limit for $\psi(4415)$ is determined to be $\Gamma_{ee}^{\psi(4415)}\mathcal{B}(\psi(4415) \to \omega\chi_{c0}) < 1.4$ eV. If we take $\Gamma(\psi(4415) \to e^+e^-) = 0.58$ keV [18], we can obtain the 90% C.L. upper limit for the branching fraction $\mathcal{B}(\psi(4415) \to \omega\chi_{c0}) < 2.4 \times 10^{-3}$. Assuming that $\omega\chi_{c0}$ comes from $Y(4220)$ and $Y(4660)$, the upper limit for $Y(4660)$ is $\Gamma_{ee}^{Y(4660)}\mathcal{B}(Y(4660) \to \omega\chi_{c0}) < 3.2$ eV. The upper limits for $Y(4360)$, $\psi(4415)$ and $Y(4660)$ are also shown in Fig. 2, and the results for $e^+e^- \to \omega\chi_{c0}$ are listed in Table I.

TABLE I

The fit results of the cross sections of $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$, the upper limits are at 90% C.L.

	χ_{c0}	χ_{c1}	χ_{c2}
$\Gamma_{ee}^{Y(4220)}\mathcal{B}(Y(4220) \to \omega\chi_{cJ})$ [eV]	2.8 ± 0.5	—	—
$\Gamma_{ee}^{Y(4360)}\mathcal{B}(Y(4360) \to \omega\chi_{cJ})$ [eV]	< 3.0	< 0.5	< 3.0
$\Gamma_{ee}^{\psi(4415)}\mathcal{B}(\psi(4415) \to \omega\chi_{cJ})$ [eV]	< 1.4	< 0.4	2.1 ± 0.3
$\mathcal{B}(\psi(4415) \to \omega\chi_{cJ})$ $(\times 10^{-3})$	< 2.4	< 0.7	3.6 ± 0.5
$\Gamma_{ee}^{Y(4660)}\mathcal{B}(Y(4660) \to \omega\chi_{cJ})$ [eV]	< 3.2	2.9 ± 0.6	< 4.7

From Fig. 1, we can see that there are obvious signals for $e^+e^- \to \omega\chi_{c1}$ around $\sqrt{s} = 4.6$ GeV, while no significant signals around $\sqrt{s} = 4.36$ and 4.42 GeV. The cross section of $e^+e^- \to \omega\chi_{c1}$ seems to be rising near 4.6 GeV, it may be from state $Y(4660)$. Assuming that the $\omega\chi_{c1}$ signals come from a single resonance $Y(4660)$, we fit the cross section with a phase-space modified BW function, the BWs mass and width are fixed at the world average values [18] for $Y(4660)$. Figure 3 shows the fit result. The fit result for the structure $Y(4660)$ is $\Gamma_{ee}^{Y(4660)}\mathcal{B}(Y(4660) \to \omega\chi_{c1}) = (2.9 \pm 0.6)$ eV. The goodness of the fit is $\chi^2/\text{n.d.f.} = 7.9/7$, corresponding to a confidence level of 34%.

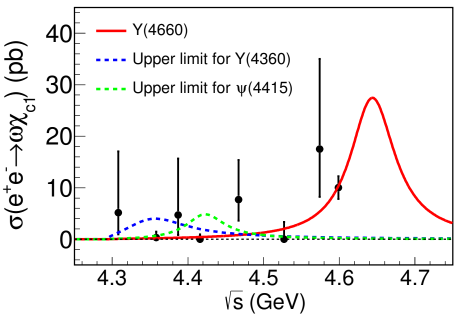

Fig. 3. (Color online) Fit to the cross section of $e^+e^- \to \omega\chi_{c1}$ from BESIII. The solid (red) curve shows the fit result using $Y(4660)$ structure, the dashed darker (blue) one is the 90% C.L. upper limit for $Y(4360)$, and the dashed lighter (green) one is the 90% C.L. upper limit for $\psi(4415)$.

Because the contributions from states $Y(4360)$ and $\psi(4415)$ are small, we also set 90% C.L. upper limits for them. Assuming that $\omega\chi_{c1}$ comes from $Y(4660)$ and $Y(4360)$, the upper limit for $Y(4360)$ is $\Gamma_{ee}^{Y(4360)}\mathcal{B}(Y(4360) \to \omega\chi_{c1}) < 0.5$ eV. We also assume that $\omega\chi_{c1}$ comes from $Y(4660)$ and $\psi(4415)$, the upper limit for $\psi(4415)$ is determined to be $\Gamma_{ee}^{\psi(4415)}\mathcal{B}(\psi(4415) \to \omega\chi_{c1}) < 0.4$ eV. If we take $\Gamma(\psi(4415) \to e^+e^-) = 0.58$ keV [18], we can obtain the 90% C.L. upper limit for the branching fraction $\mathcal{B}(\psi(4415) \to \omega\chi_{c1}) < 0.7 \times 10^{-3}$. The upper limits for $Y(4360)$ and $\psi(4415)$ are also shown in Fig. 3, and the results for $e^+e^- \to \omega\chi_{c1}$ are also listed in Table I.

From Fig. 1, we can see that there are obvious signals for $e^+e^- \to \omega\chi_{c2}$ around $\sqrt{s} = 4.42$ GeV, while signals are not significant around $\sqrt{s} = 4.36$ and 4.6 GeV. It seems there is an enhancement around 4.42 GeV, $\omega\chi_{c2}$ may be from state $\psi(4415)$. Assuming that the $\omega\chi_{c2}$ signals come from a single resonance $\psi(4415)$, we fit the cross section with a phase-space modified BW function, the BWs mass and width are fixed at the world average values [18] for $\psi(4415)$. Figure 4 shows the fit result. The fit result for the structure $\psi(4415)$ is $\Gamma_{ee}^{\psi(4415)}\mathcal{B}(\psi(4415) \to \omega\chi_{c2}) = (2.1 \pm 0.3)$ eV. If we take $\Gamma(\psi(4415) \to e^+e^-) = 0.58$ keV [18], we can obtain $\mathcal{B}(\psi(4415) \to \omega\chi_{c2}) = (3.6 \pm 0.5) \times 10^{-3}$. The goodness of the fit is $\chi^2/\text{n.d.f.} = 11.3/6$, corresponding to a confidence level of 8%.

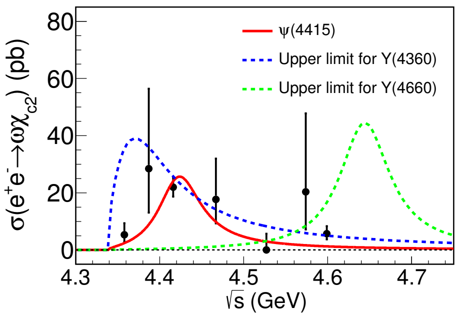

Fig. 4. (Color online) Fit to the cross section of $e^+e^- \to \omega\chi_{c2}$ from BESIII. The solid (red) curve shows the fit result using $\psi(4415)$ structure, the dashed darker (blue) one is the 90% C.L. upper limit for $Y(4360)$, and the dashed lighter (green) one is the 90% C.L. upper limit for $Y(4660)$.

Because the signals are not significant around $\sqrt{s} = 4.36$ and 4.6 GeV, we also set 90% C.L. upper limits for $Y(4360)$ and $Y(4660)$. Assuming that $\omega\chi_{c2}$ comes from $\psi(4415)$ and $Y(4360)$, the upper limit for $Y(4360)$ is $\Gamma_{ee}^{Y(4360)}\mathcal{B}(Y(4360) \to \omega\chi_{c2}) < 3.0$ eV. We also assume that $\omega\chi_{c2}$ comes from $\psi(4415)$ and $Y(4660)$, the upper limit for $Y(4660)$ is determined to be $\Gamma_{ee}^{Y(4660)}\mathcal{B}(Y(4660) \to \omega\chi_{c2}) < 4.7$ eV. The upper limits for $Y(4360)$ and $Y(4660)$ are also shown in Fig. 4, and the results for $e^+e^- \to \omega\chi_{c2}$ are also listed in Table I.

If we only use a $\psi(4415)$ to fit the cross section of $e^+e^- \to \omega\chi_{c2}$, the goodness of the fit is $\chi^2/\text{n.d.f.} = 11.3/6$. The goodness of the fit is relatively large, it indicates there may be contributions from other charmonium (-like) states. Assuming that $\omega\chi_{c2}$ comes from two resonances $\psi(4415)$ and $Y(4360)$, we fit the cross section with coherent sum of two constant width relativistic BW function. Figure 5 shows the fit result. There are two solutions with the same fit quality, the results are listed in Table II. The goodness of the fit is $\chi^2/\text{n.d.f.} = 5.9/4$, corresponding to a confidence level of 21%. Comparing the χ^2s change and taking into account the change of the number of degree of freedom, the statistical significance of the $Y(4360)$ resonance is 1.8σ. We also try to assume that $\omega\chi_{c2}$ comes from two resonances $\psi(4415)$ and $Y(4660)$, the fit result is also shown in Fig. 5. There are two solutions with the same fit quality, the results are also listed in Table II. The goodness of the fit is $\chi^2/\text{n.d.f.} = 5.9/4$, corresponding to a confidence level of 21%.

Comparing the χ^2s change and taking into account the change of the number of degree of freedom, the statistical significance of the $Y(4660)$ resonance is 1.8σ. The goodness of the fits is the same with the two assumptions. With more data sample in the future, especially the data above 4.6 GeV, it can be used to decide which hypothesis is reasonable.

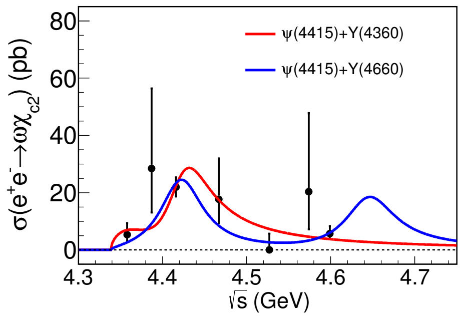

Fig. 5. (Color online) Fit to the cross section of $e^+e^- \to \omega\chi_{c2}$ from BESIII. The solid lighter (red) curve shows the fit result using $\psi(4415)$ and $Y(4360)$, and solid darker (blue) curve shows the fit result using $\psi(4415)$ and $Y(4660)$.

TABLE II

The fit results of the cross section of $e^+e^- \to \omega\chi_{c2}$. Solution I shows the results using $\psi(4415)$ and $Y(4360)$ to fit, and Solution II the results using $\psi(4415)$ and $Y(4660)$ to fit.

	$\psi(4415)+Y(4360)$		$\psi(4415)+Y(4660)$	
	Solution I	Solution II	Solution I	Solution II
$\Gamma_{ee}^{\psi(4415)}\mathcal{B}(\psi(4415)\to\omega\chi_{c2})$ [eV]	1.6±1.0	7.1±1.2	1.8±0.3	2.5±0.4
$\mathcal{B}(\psi(4415)\to\omega\chi_{cJ})$ $(\times 10^{-3})$	2.8±1.7	12.2±2.1	3.1±0.5	4.3±0.7
$\Gamma_{ee}^{Y(4360)/Y(4660)}\mathcal{B}(Y(4360)/Y(4660)\to\omega\chi_{c2})$ [eV]	0.6±0.4	2.2±0.8	1.4±2.0	3.0±2.2
ϕ_1	0.53±0.60	2.16±0.15	0.75±1.47	−1.58±0.88

In summary, we try to search for vector charmonium(-like) states $Y(4220)$, $Y(4360)$, $\psi(4415)$ and $Y(4660)$ in the $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ line shapes. The $\omega\chi_{c0}$ comes mainly from $Y(4220)$, $\omega\chi_{c1}$ probably comes mainly from $Y(4660)$ and $\omega\chi_{c2}$ probably comes mainly from $\psi(4415)$. More data samples are needed to confirm these assumptions, and it is very important to confirm the structure above 4.6 GeV in $e^+e^- \to \omega\chi_{c1}$. For the charmonium(-like) states that are not significant in the $e^+e^- \to \omega\chi_{cJ(J=0,1,2)}$ line shape, we also give the 90% C.L. upper limits on the electron partial width multiplied by branching fraction. The results are listed in Table I. We also try to use $\psi(4415)$ and $Y(4360)/Y(4660)$ to fit the cross section of $e^+e^- \to \omega\chi_{c2}$, the results are listed in Table II. It will be helpful to study the nature of charmonium(-like) states. More high-precision measurements around this energy region are desired to better understand these results, this can be achieved in BESIII and BelleII experiments in the future.

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