Search for $\psi(4S)\to\eta J/\psi$ in $B^\pm\to\eta J/\psi K^\pm$ and $e^+e^-\to\eta J/\psi$ processes *

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Abstract: We search for the $\psi(4S)$ state in the $B^\pm\to\eta J/\psi K^\pm$ and $e^+e^-\to\eta J/\psi$ processes based on the Belle measurements with the assumed mass $M=(4230\pm8)$ MeV/c^2 and width $\Gamma=(38\pm12)$ MeV. No significant signal is observed in the $\eta J/\psi$ mass spectra. The 90% confidence level upper limit on the product branching fraction $\mathcal{B}(B^\pm\to\psi(4S)K^\pm)\mathcal{B}(\psi(4S)\to\eta J/\psi)<6.8\times10^{-6}$ is obtained in the $B^\pm\to\eta J/\psi K^\pm$ decays. By assuming the partial width of $\psi(4S)\to e^+e^-$ to be 0.63 keV, a branching fraction limit $\mathcal{B}(\psi(4S)\to\eta J/\psi)<1.3\%$ is obtained at the 90% confidence level in $e^+e^-\to\eta J/\psi$, which is consistent with the theoretical prediction.

Keywords: $\psi(4S)$, $\eta J/\psi$, upper limit, branching fraction

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1 Introduction

Potential models predict some charmonium states above the $D\bar{D}$ threshold, but the number of observed states in experiments is more than the number predicted. The states which have been seen beyond the theoretical predictions are normally referred to as exotic states or XYZ particles. Many XYZ states have been announced in various processes, for example, the observation of X(3872) in B decays [1], the Y(4260) [2], Y(4360) [3] and Y(4660) [4] in e^+e^- annihilation, and the X(3915) [5] observed in the two-photon process.

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, such as $\eta_c(3S)$, $\eta_c(4S)$, $\psi(4S)$ and $\psi(5S)$. To some degree, some XYZ states are regarded as candidates for these unfound predicted states.

Searching for these missing predicted states is very helpful to test the potential models. When checking the mass spectra of the observed charmonia with spin-parity $J^{PC}=1^{--}$ and comparing them with those of the corresponding bottomonia, there might be a charmonium state $\psi(4S)$ at about 4.2 GeV/c^2 compared to the $\Upsilon(4S)$ state [6]. The authors in Ref. [6] predicted that this missing charmonium state has a mass of 4.263 GeV/c^2 and a very narrow width. As a state with the same spin-parity 1^{--}, the Y(4220) [7] may be a good candidate for the $\psi(4S)$ state.

Recently, the BESIII Collaboration performed a study on the decay $e^+e^-\to\omega\chi_{cJ}$ (J = 0,1,2) [7], where the Born cross sections at nine energy points were measured. When using a Breit–Wigner (BW) function to fit the experimental data of $e^+e^-\to\omega\chi_{c0}$, a resonant structure with mass $M=(4230\pm8)$ MeV/c^2 and width $\Gamma=(38\pm12)$ MeV was observed with a statistical significance more than 9σ. However, for the remaining processes $e^+e^-\to\omega\chi_{c1}$ and $e^+e^-\to\omega\chi_{c2}$, there were no significant signals.

To understand this novel phenomenon, different explanations of this resonance were given, which included a tetraquark state [8], the missing higher charmonium state $\psi(4S)$ [9], and the known charmonium resonance $\psi(4160)$ [10].

The authors in Ref. [9] checked the thresholds of $\omega\chi_{c0}$, $\omega\chi_{c1}$ and $\omega\chi_{c2}$, which are 4.197 GeV/c^2, 4.293 GeV/c^2 and 4.338 GeV/c^2, respectively. The central mass of $\psi(4S)$ is just above the $\omega\chi_{c0}$ threshold and below the $\omega\chi_{c1,2}$ thresholds. Accordingly the newly observed structure in $e^+e^-\to\omega\chi_{c0}$ could be the missing charmonium $\psi(4S)$ state, and the $e^+e^-\to\omega\chi_{c1,2}$ processes are

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kinematically forbidden to ψ(4S). Stimulated by this, the authors estimated the meson loop contribution to ψ(4S)→$\omega\chi_{c0}$ and found the evaluation can overlap with the experimental data in a reasonable parameter range. As a typical transition accessible by experiment, the decay ψ(4S)→ηJ/ψ similar to ψ(4S)→$\omega\chi_{c0}$ can occur. So the authors in Ref. [9] also extended the theoretical calculation to ψ(4S)→ηJ/ψ and predicted the upper limit on the branching fraction of ψ(4S)→ηJ/ψ to be less than 1.9×10^{-3} via the hadronic loop mechanism [9].

As indicated in Ref. [9], the predicted upper limit of ψ(4S)→ηJ/ψ can be accessible at Belle and the forthcoming BelleII. We noticed that the Belle experiment previously measured the $B^{\pm}\to\eta J/\psi K^{\pm}$ [11] and $e^+e^-\to\eta J/\psi$ [12] processes, where the ηJ/ψ invariant mass distributions were given. Hence, in this work we fit the ηJ/ψ mass spectra from the $B^{\pm}\to\eta J/\psi K^{\pm}$ and $e^+e^-\to\eta J/\psi$ processes to search for the ψ(4S) state. The experimental measurements can be taken as a test of the theoretical calculation.

This work is organized as follows. We present the detailed fit results to the ηJ/ψ mass spectra from $B^{\pm}\to\eta J/\psi K^{\pm}$ and $e^+e^-\to\eta J/\psi$ processes with the ψ(4S) state included in Sec. 2 and Sec. 3. If no clear ψ(4S) signal is observed, the branching fraction limits at the 90% confidence level (C.L.) will be given with the systematic errors included. The last section ends with the conclusion and discussion.

2 Search for ψ(4S) in B decays

Using 772×10^6 $B\bar{B}$ pairs collected with the Belle detector, the decays $B^{\pm}\to\eta J/\psi K^{\pm}$ were studied to search for a new narrow charmonium(-like) state X in the ηJ/ψ mass spectrum, where the J/ψ and η mesons were reconstructed by a lepton-pair $\ell^+\ell^-$ (ℓ = e, μ) and two photons [11]. Except for the known $\psi'\to\eta J/\psi$ decay, no significant narrow excess was found in the ηJ/ψ mass spectrum.

Figure 1 shows the ηJ/ψ mass distribution of interest after all the event selection requirements are applied. A binned maximum likelihood fit to the ηJ/ψ mass distribution is performed to extract the signal and background yields. A BW function (mass and width fixed at 4.23 GeV/c^2 and 38 MeV [9]) is convolved with a Gaussian function (the mass resolution is about 11 MeV/c^2) as the ψ(4S) signal shape and a second polynomial function is taken as the background shape. The fit range and results to the ηJ/ψ mass spectrum are shown in Fig. 1.

From the fit, we obtain 5.9±5.5 signal events, with a statistical significance of 0.9σ, from the difference of the logarithmic likelihoods, $-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$, taking the difference in the number of degrees of freedom (Δndf=1) in the fits into account, where $\mathcal{L}_0$ and $\mathcal{L}_{\max}$ are the likelihoods of the fits without and with a resonance component, respectively.

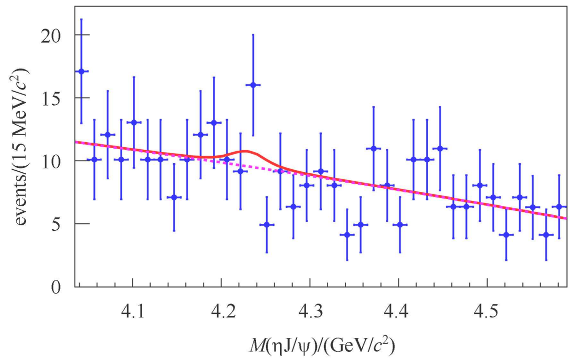

Fig. 1. (color online) The ηJ/ψ invariant mass distribution from $B^{\pm}\to\eta J/\psi K^{\pm}$ decays. The dots with error bars are from data, the solid curve is the best fit for the total signal and the dotted line shows the fitted background shape.

We determine a Bayesian 90% C.L. upper limit on the number of ψ(4S) signal events ($N_{\rm sig}$) by finding the value $N^{\rm UP}_{\rm sig}$ such that $\int_0^{N^{\rm UP}_{\rm sig}}\mathcal{L}{\rm d}N_{\rm sig}/\int_0^{\infty}\mathcal{L}{\rm d}N_{\rm sig}=0.90$, where $N_{\rm sig}$ is the number of ψ(4S) signal events and $\mathcal{L}$ is the value of the likelihood as a function of $N_{\rm sig}$. To take into account the systematic uncertainty, the above likelihood is convolved with a Gaussian function whose width equals the total systematic uncertainty described below. The upper limit on the number of ψ(4S) signal events is 22.7 at 90% C.L.

There are several sources of systematic error for the branching fraction measurement. Most of the systematic errors are the same as those in Ref. [11], except that the dominant uncertainty associated with the fitting procedure is different, which is estimated by changing the order of the background polynomial, the range of the fit, the ψ(4S) mass and width by $\pm1\sigma$. Finally, the uncertainty due to the fitting procedure is 11%. Assuming all the sources are independent and adding them in quadrature, the final total systematic uncertainties are summarized in Table 1.

Table 1. Relative systematic errors (%) on the product of the branching fraction $\mathcal{B}(B^{\pm}\to\psi(4S)K^{\pm})\mathcal{B}(\psi(4S)\to\eta J/\psi)$.

source	relative error(%)
tracking efficiency	1.1
lepton identification	2.4
charged kaon identification	1.4
$\eta\to\gamma\gamma$ efficiency	3.0
signal MC simulation statistics	0.5
secondary $\mathcal{B}$	0.7
$N_{B\bar{B}}$	1.4
fitting procedure	11
total	12

The 90% C.L. upper limit is set on the product branching fraction $\mathcal{B}(\mathrm{B}^{\pm}\to\psi(4S)\mathrm{K}^{\pm})\mathcal{B}(\psi(4S)\to\eta\mathrm{J}/\psi)$ using

$$B^{\mathrm{UP}}=\frac{N_{\mathrm{sig}}^{\mathrm{UP}}}{N_{\mathrm{B\bar{B}}}\times\epsilon\times\mathcal{B}(\mathrm{J}/\psi\to\ell^{+}\ell^{-})\times\mathcal{B}(\eta\to\gamma\gamma)},$$

where $N_{\mathrm{sig}}^{\mathrm{UP}}$, $N_{\mathrm{B\bar{B}}}$, ϵ, $\mathcal{B}(\mathrm{J}/\psi\to\ell^{+}\ell^{-})$ and $\mathcal{B}(\eta\to\gamma\gamma)$ are the upper limit on the number of $\psi(4S)$ signal events at 90% C.L., the number of $\mathrm{B\bar{B}}$ pairs, the corrected detection efficiency of 9.23% at 4.23 GeV/c^2 obtained from the fitted efficiency curve using the efficiencies at ψ', $\psi(4040)$ and $\psi(4160)$ points [11], the branching fractions of J/ψ to lepton pair and η to two photons [13], respectively. Finally, the 90% C.L. upper limit on the product branching fraction $\mathcal{B}(\mathrm{B}^{\pm}\to\psi(4S)\mathrm{K}^{\pm})\mathcal{B}(\psi(4S)\to\eta\mathrm{J}/\psi)$ is found to be 6.8×10^{-6}.

3 Search for $\psi(4S)$ in $\mathrm{e}^{+}\mathrm{e}^{-}\to\eta\mathrm{J}/\psi$

The cross section for $\mathrm{e}^{+}\mathrm{e}^{-}\to\eta\mathrm{J}/\psi$ between $\sqrt{s}=3.8$ and 5.3 GeV was measured using 980 fb^{-1} of Belle data, where the η was reconstructed with its $\gamma\gamma$ and $\pi^{+}\pi^{-}\pi^{0}$ decays and J/ψ was reconstructed via its leptonic decays. Two distinct resonant structures, the $\psi(4040)$ and $\psi(4160)$, were observed [12].

To obtain the transition rates of $\psi(4040)$ and $\psi(4160)$ to the $\eta\mathrm{J}/\psi$ final state, an unbinned maximum likelihood fit was performed to the $\eta\mathrm{J}/\psi$ mass spectra from the signal candidate events and the η and J/ψ sideband events simultaneously [12]. The fit to the signal events includes two coherent P-wave BW functions convolved by the effective luminosity and efficiency curve for $\psi(4040)$ and $\psi(4160)$ signals and an incoherent second-order polynomial background; the fit to the sideband events includes the same background function only. Due to the low statistics, the masses and widths of the $\psi(4040)$ and $\psi(4160)$ were fixed [14] and the effects of mass resolution were small and therefore were ignored [12].

Similarly here, to obtain the transition rate of $\psi(4S)$ to $\eta\mathrm{J}/\psi$ final state, a binned maximum likelihood fit with three coherent P-wave BW functions for $\psi(4040)$, $\psi(4160)$ and $\psi(4S)$ is applied to the $\mathrm{e}^{+}\mathrm{e}^{-}\to\eta\mathrm{J}/\psi$ cross sections directly, as shown in Fig. 2. In the fits, besides the masses and widths of $\psi(4040)$ and $\psi(4160)$ being fixed [14], the $\psi(4S)$ parameters are also fixed [9]. Figure 2 and Table 2 show the fit results. There are four solutions with equally good fit quality. The results of $\mathcal{B}\Gamma_{\mathrm{e^+e^-}}$ for $\psi(4040)$ and $\psi(4160)$ are consistent with the published results within errors [12]. The significance of the $\psi(4S)$ is estimated by comparing the likelihood of fits with and without $\psi(4S)$ included. We obtain a statistical significance of 2.6σ. The most conservative upper limit with the systematic errors included on $\mathcal{B}(\psi(4S)\to\eta\mathrm{J}/\psi)\Gamma_{\mathrm{e^+e^-}}^{\psi(4S)}$ is obtained to be 8.2 eV at 90% C.L., which corresponds to Solution III in Fig. 2(c).

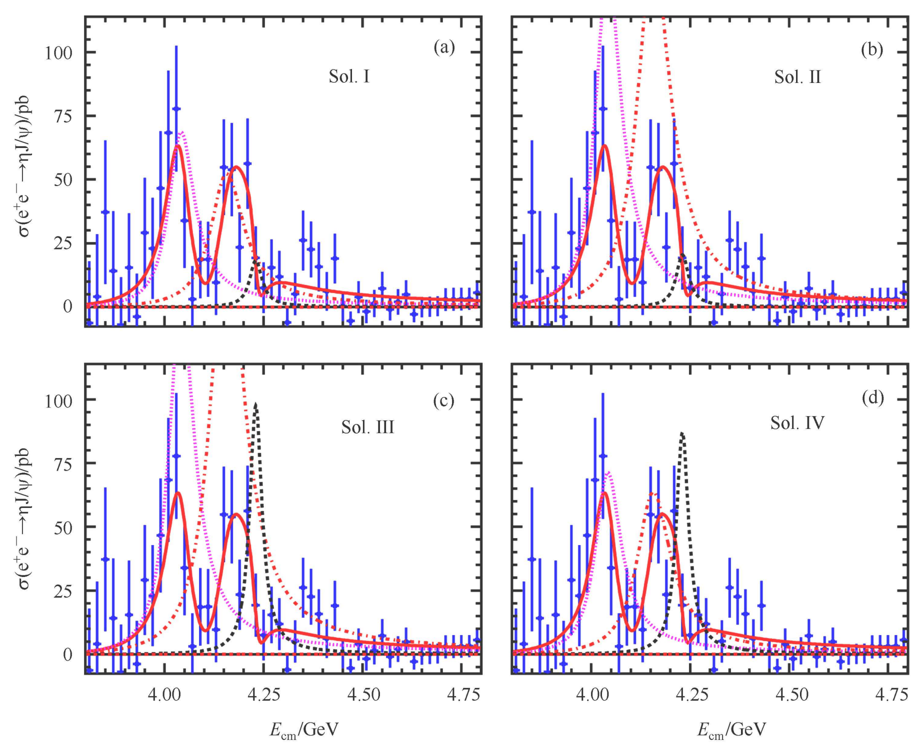

Fig. 2. (color online) The $\mathrm{e}^{+}\mathrm{e}^{-}\to\eta\mathrm{J}/\psi$ cross section distributions and the fit results described in the text. There are four solutions with the coherent $\psi(4040)$, $\psi(4160)$ and $\psi(4S)$ signals. The curves show the best fit for the measured cross sections and the contribution from each BW component. The interference term for each solution is not shown.

Table 2. Results of the fits to the $e^+e^- \to \eta J/\psi$ cross sections using three coherent resonances: $\psi(4040)$, $\psi(4160)$ and $\psi(4S)$. The errors are statistical only. M, Γ, and $\mathcal{B}\Gamma_{e^+e^-}$ are the mass (in MeV/c^2), total width (in MeV), product of the branching fraction to $\eta J/\psi$ and the e^+e^- partial width (in eV), respectively. ϕ_1 is the relative phase between the $\psi(4040)$ and $\psi(4160)$ (in degrees) and ϕ_2 is the relative phase between the $\psi(4160)$ and $\psi(4S)$ (in degrees).

	solution I	solution II	solution III	solution IV
$M_{\psi(4040)}$	4039(fixed)			
$\Gamma_{\psi(4040)}$	80(fixed)			
$\mathcal{B}(\psi(4040)\to\eta J/\psi)\Gamma^{\psi(4040)}_{e^+e^-}$	6.1 ± 1.1	11.8 ± 1.4	12.2 ± 1.5	6.3 ± 1.1
$M_{\psi(4160)}$	4153(fixed)			
$\Gamma_{\psi(4160)}$	103(fixed)			
$\mathcal{B}(\psi(4160)\to\eta J/\psi)\Gamma^{\psi(4160)}_{e^+e^-}$	6.3 ± 1.6	16.7 ± 2.2	20.4 ± 2.4	7.7 ± 1.7
$M_{\psi(4S)}$	4230(fixed)			
$\Gamma_{\psi(4S)}$	38(fixed)			
$\mathcal{B}(\psi(4S)\to\eta J/\psi)\Gamma^{\psi(4S)}_{e^+e^-}$	0.8 ± 0.6	0.9 ± 0.7	4.5 ± 1.3	4.0 ± 1.2
ϕ_1	320 ± 12	258 ± 6	262 ± 5	324 ± 12
ϕ_2	171 ± 16	117 ± 17	142 ± 8	197 ± 12

Most of the systematic errors in the $\mathcal{B}(\psi(4S)\to\eta J/\psi)\Gamma^{\psi(4S)}_{e^+e^-}$ measurement are the same as those in Ref. [12] except the dominant systematic error from fit uncertainty (64%), which includes the uncertainties on the mass and width of $\psi(4S)$ state by changing the nominal values by 1σ [9], and the fit range. Assuming all the sources are independent and adding them in quadrature, we obtain total systematic error in $\mathcal{B}\Gamma_{e^+e^-}$ of 65% for $\psi(4S)$, as shown in Table 3.

Table 3. Relative systematic errors (in %) in the $\mathcal{B}(\psi(4S)\to\eta J/\psi)\Gamma^{\psi(4S)}_{e^+e^-}$ measurement.

source	relative error(%)
particle identification	5.5
tracking efficiency	1.4
photon reconstruction	4.0
J/ψ, η mass etc requirements	2.6
luminosity measurement	1.4
MC generator	1.0
trigger simulation	2.0
intermediate decay branching fractions	1.6
signal MC simulation statistics	0.2
fit uncertainty	64
total	65

In Refs. [15, 16], the partial width of $\psi(4S)\to e^+e^-$ was estimated, i.e., $\Gamma(\psi(4S)\to e^+e^-)=0.63$ keV [15] and $\Gamma(\psi(4S)\to e^+e^-)=0.66$ keV [16]. If we take the lower theoretical calculation $\Gamma(\psi(4S)\to e^+e^-)=0.63$ keV [15], we can obtain the conservative upper limit on branching fraction $\mathcal{B}(\psi(4S)\to\eta J/\psi)$ at 90% C.L., i.e.,

$$\mathcal{B}(\psi(4S)\to\eta J/\psi)<1.3\%\ ,$$

which does not contradict the theoretical prediction of 1.9×10^{-3} [9].

4 Summary

In summary, we search for the $\psi(4S)$ state in the $B^\pm\to\eta J/\psi K^\pm$ and $e^+e^-\to\eta J/\psi$ processes based on the Belle measurements with the assumed mass $M=(4230\pm8)$ MeV/c^2 and width $\Gamma=(38\pm12)$ MeV. The $\eta J/\psi$ mass spectrum from B decays and the cross sections of $e^+e^-\to\eta J/\psi$ are fitted with the $\psi(4S)$ resonance included for the first time. No significant signal is observed, and 90% C.L. upper limits of $\mathcal{B}(B^\pm\to\psi(4S))\mathcal{B}(\psi(4S)\to\eta J/\psi K^\pm)<6.8\times10^{-6}$ and $\mathcal{B}(\psi(4S)\to\eta J/\psi)\Gamma^{\psi(4S)}_{e^+e^-}<8.2$ eV are obtained. With the $\Gamma(\psi(4S)\to e^+e^-)=0.63$ keV [15] as input, we have $\mathcal{B}(\psi(4S)\to\eta J/\psi)<1.3\%$, which is almost one order higher in magnitude than the theoretical prediction [9].

The expected integrated luminosity at the BelleII experiment is 50 ab^{-1} in 2024, which is about 50 times the current total integrated luminosity at Belle. With this huge data sample, the expected upper limit on $\mathcal{B}(\psi(4S)\to\eta J/\psi)$ will be 1.9×10^{-3} if it scales as $1/\sqrt{L}$, where L is the integrated luminosity, and can therefore reach the theoretical prediction level.

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