Chinese Physics Letters **40**, 121301 (2023) **Review**

Status and Prospects of Exotic Hadrons at Belle Ⅱ

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(Received 29 September 2023; accepted manuscript online 3 November 2023)

In the past 20 years, many new hadrons that are difficult to explain within the conventional quark model have been discovered in the quarkonium region; these are called exotic hadrons. The Belle Ⅱ experiment, as the next-generation B factory, provides a good platform for exploring them. The charmonium-like states can be produced at Belle Ⅱ in several ways, such as B meson decays, initial-state radiation processes, two-photon collisions and double charmonium production. Bottomonium-like states can be produced directly in e^+e^- colliding energies at Belle Ⅱ with low continuum backgrounds. Belle Ⅱ plans to perform a high-statistics energy scan from the $B\bar{B}$ threshold up to the highest possible energy of 11.24 GeV to search for new Y_b states with $J^{\rm PC} = 1^{--}$, X_b [the bottom counterpart of $\chi_{c1}(3872)$, also known as $X(3872)$] and partners of Z_b states. We give a mini-review on the status and prospects of exotic hadrons at Belle Ⅱ.

DOI: 10.1088/0256-307X/40/12/121301

1. Introduction. Hadrons are composite subatomic particles made of two or more quarks held together by the strong interaction; they can be described by quantum chromodynamics (QCD) in the Standard Model. At high energies, asymptotic freedom guarantees that properties of QCD can be computed in the weak-coupling perturbation theory,[1,2] while at low energies the weak-coupling perturbation theory fails to interpret the color confinement.[3] Therefore, research of hadrons in charmonium and bottomonium regions offers many opportunities for insight into the nonperturbative behavior of QCD.

Besides conventional mesons composed of $q\bar{q}$ and baryons with qqq, multiquark states with $qq\bar{q}\bar{q}$ or $qqqq\bar{q}$ were proposed by Gell-Mann in 1964 in one of the first publications on the quark model.[4] In this review, we refer to any state which does not coincide with the expectations for an ordinary $q\bar{q}$ or qqq hadron in the quark model as being 'exotic'. In the charmonium and bottomonium regions, the exotic hadrons are also called charmonium-like and bottomonium-like states.

There was no progress in searching for exotic hadrons until the observation of $X(3872)$ in the $\pi^+\pi^- J/\psi$ final states by Belle in 2003.[5] Here, $X(3872)$ denotes $\chi_{c1}(3872)$ in the particle data group (PDG).[6] We use $X(3872)$ instead of $\chi_{c1}(3872)$ hereafter. The properties of $X(3872)$ did not fit those of an ordinary charmonium. Since then, many new exotic hadrons have been discovered in various experiments.[3,7] Among them, the Belle experiment made many contributions. Besides $X(3872)$, the first charged charmonium-like state, $Z_c(4430)^{\pm} \to \pi^{\pm}\psi(2S)$,[8] was observed by Belle in B decays in 2007, and was confirmed by LHCb seven years later.[9] Almost at the same time, $Z_c(3900)^{\pm} \to \pi^{\pm} J/\psi$ was discovered by BESⅢ in direct e^+e^- annihilations and by Belle in the initial state radiation (ISR) process, and is regarded as an alternative tetraquark state.[10,11] Up to date, only two bottomonium-like states, $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$, have been discovered.[12] They were first found in $\pi^{\pm}\Upsilon(nS)$ ($n = 1, 2, 3$) final states by Belle using $\Upsilon(5S)$ data samples.

The Belle Ⅱ experiment started to collect "physics" data in 2019. In June 2022, the accelerator SuperKEKB achieved the highest ever instantaneous luminosity of $4.7 \times 10^{34}\,{\rm cm}^{-2}{\cdot}{\rm s}^{-1}$. The data collected at Belle Ⅱ by the end of 2023 correspond to an integrated luminosity of 427.79 fb^{-1}. The integrated luminosity is expected to increase drastically in the following years, and will ultimately reach 50 ab^{-1} around 2034. With large data samples, the experimental studies on exotic hadrons at Belle Ⅱ can proceed: searches for new exotic hadrons and expected partners of existing exotic hadrons, searches for new decay channels of known states and detailed measurements of all accessible properties, including spin-parities, absolute branching fractions, line-shapes, etc. We do not discuss exotic baryons due to the limited conditions at Belle Ⅱ.

2. Achievements at Belle. The Belle experiment ran at the KEKB e^+e^- asymmetric energy collider at the KEK Laboratory, Tsukuba, Japan between 1999 and 2010.[13–15] Many data samples at Belle were recorded on or near the $\Upsilon(4S)$ resonance, where copious $B\bar{B}$ pairs used to study B physics are produced. In addition, Belle collected a series of special data sets at $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(10860)$

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resonances. The data samples recorded at Belle are detailedly given in Table 1.[16] The total integrated luminosity reached approximately $1\,\text{ab}^{-1}$. All the data sets were used to explore hadron spectroscopy, and a large number of new conventional quarkonia and some exotic hadrons were found using these samples.

Belle is constantly enriching hadron spectroscopy. As shown in Fig. 1,[17] many quarkonium(-like) states were observed at Belle, including long-term missing conventional quarkonia and new exotic hadrons of X, Y, Z_c and Z_b states. In the following, we introduce three outstanding achievements on exotic hadrons at Belle.

Table 1. Integrated luminosities of Belle data samples. The scan data were collected with approximately $1\,\text{fb}^{-1}$ per point in the $\Upsilon(10860)$ and $\Upsilon(11020)$ energy ranges from 10.63 to 11.02 GeV.[16]

Resonance	On-peak luminosity (fb^{-1})	Off-peak luminosity (fb^{-1})	Number of accumulated events
$\Upsilon(1S)$	5.7	1.8	102×10^6
$\Upsilon(2S)$	24.9	1.7	158×10^6
$\Upsilon(3S)$	2.9	0.25	11×10^6
$\Upsilon(4S)$	711.0	89.4	$772\times10^6\,B\bar{B}$
$\Upsilon(5S)$	121.4	1.7	$7\times10^6\,B_s\bar{B}_s$
Energy scan		27.6	

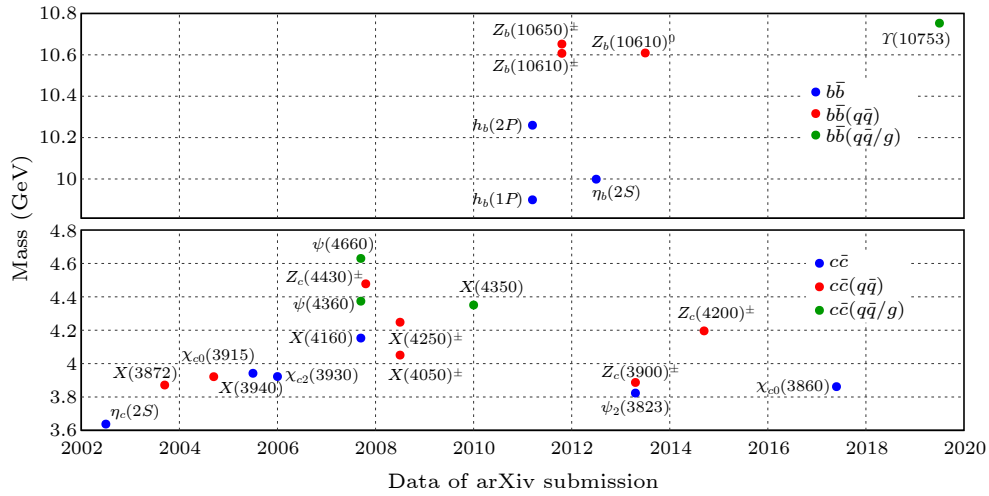

Fig. 1. Quarkonium(-like) states observed by Belle against year of observation.[17]

In 2003, Belle observed a narrow charmonium-like state decaying into $\pi^+\pi^- J/\psi$ with a mass of $3872.0 \pm 0.8\,\text{MeV}/c^2$ in $B^\pm \to K^\pm\pi^+\pi^- J/\psi$.[5] This is the first state with unconventional charmonium properties, thus opening a new era for the study of exotic hadrons. $X(3872)$ was subsequently confirmed by several other experiments.[18–20] $J^{\text{PC}} = 1^{++}$ was determined by LHCb via performing a five-dimensional angular correlation analysis in B decays.[21] $X(3872)$ is still one of the most interesting exotic meson candidates because of its unexpected properties. The mass of $X(3872)$ is close to the $D\bar{D}^{(*)}$ threshold, and its width is very narrow. Such a property is very different from the excited ψ states, such as $\psi(3770)$, $\psi(4040)$, and $\psi(4160)$, which decay into $D^{(*)}\bar{D}^{(*)}$ with large branching fractions, but their widths are very large. The enhancement of isospin-violating $J/\psi\rho$ decay was observed. Very recently, Belle determined that the lower limit on the $D\bar{D}^*$ coupling constant is 0.094 at a 90% credibility level, which implies that the partial width of $D\bar{D}^*$ in $X(3872)$ decays is much larger than those of $J/\psi\rho$, $J/\psi\omega$, and radiative decay modes.[22]

Searching for charged charmonium-like states is one of the most promising ways for studying exotic hadrons, since such a state must contain at least four quarks and thus cannot be a conventional quark–antiquark meson. The first charged charmonium-like state, $Z_c(4430)^\pm$, was reported in the $\pi^\pm\psi(2S)$ mass spectrum in $B \to K\pi^\pm\psi(2S)$ decays at Belle in 2007.[8] It was not confirmed by LHCb until 7 years later.[9] Unlike $Z_c(4430)^\pm$, the $Z_c(3900)$ state decaying into $\pi^\pm J/\psi$ was observed simultaneously by BESIII and Belle.[10,11] $Z_c(4200)^+ \to \pi^+ J/\psi$ with $J^{\text{P}} = 1^+$ was observed by performing an amplitude analysis of $\bar{B}^0 \to J/\psi K^-\pi^+$ decays in four dimensions by Belle,[23] which has been confirmed by LHCb.[24]

In comparison with the number of charmonium-like states from PDG,[25] the number of bottomonium-like states is smaller due to lower production rates and limited experimental conditions. So far, only two bottomonium-like states have been observed: $Z_b(10610)$ and $Z_b(10650)$. They were discovered by Belle using only $\Upsilon(5S)$ on-

resonance and scan data samples.[12,26–29] $Z_b(10610)^+$ and $Z_b(10650)^+$ can decay into $\pi^+\Upsilon(nS)$ ($n = 1, 2, 3$), $\pi^+ h_b(mP)$ ($m = 1, 2$) and $B^{(*)+}\bar{B}^{*0}$.[12,26–28] The decay modes of $Z_b(10610)^+ \to B^+\bar{B}^{*0}$ and $Z_b(10650)^+ \to B^{*+}\bar{B}^{*0}$ are dominant.[28] The neutral partner of $Z_b(10610)^+$ was observed as well in its $\pi^0\Upsilon(2S)$ and $\pi^0\Upsilon(3S)$ decay modes.[29]

3. Belle Ⅱ Experiment and Data Collection. Belle Ⅱ, the first super B-factory experiment, operates at the asymmetric-energy e^+e^- SuperKEKB collider.[30] Two beams with energies of 7.0 GeV and 4.0 GeV collide at an angle of 83 mrad (22 mrad in KEKB). It has several Belle subdetectors in an upgraded version together with others newly developed for Belle Ⅱ.[31] The vertex detector consists of pixel sensors and double-sided silicon vertex detectors. The central drift chamber is surrounded by two types of Cherenkov light counters: an azimuthal array of time-of-propagation detectors for the barrel region and an aerogel ring-imaging Cherenkov detector for the forward endcap region to the electron beam. The Belle electromagnetic CsI(Tl) crystal calorimeter, with upgraded electronics, is reused in Belle Ⅱ along with the solenoid and the iron flux return yoke. The muon and K_L^0 identification system with upgraded glass-electrode resistive plate chambers and scintillator is the outermost and only sub-detector outside the magnet.

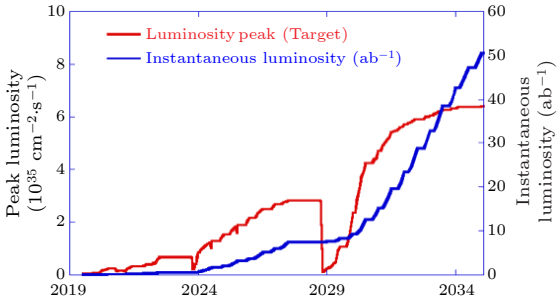

Fig. 2. Data collection plan at Belle Ⅱ.[32] The red line shows the instantaneous luminosity and the blue line shows the integrated luminosity.

Taking a "nano-beam" scheme of reduction in the beam size and increase in the currents, the luminosity at SuperKEKB is expected to increase drastically.[30] Figure 2 shows the data collection plan at Belle Ⅱ.[32] Belle Ⅱ's goal is to accumulate 50 ab^{-1} of data until 2035.[32,33] This schedule includes two long shutdowns (LS1 and LS2) for detector upgrades. During LS1, Belle Ⅱ will complete the installation of the second layer of the pixel-based inner vertex detector. For LS2, major upgrades to the detector are being considered, along with extensive upgrades to the accelerator. After 2023, the number of data collected at Belle Ⅱ will increase sharply with the completion of LS1. Although the data will mainly be recorded at $\Upsilon(4S)$ resonance, data collection at other energy points with substantial statistics can be guaranteed. It is worth mentioning that all the data at Belle Ⅱ can be used to probe the exotic hadrons discussed below.

4. Prospects for Charmonium-Like States at Belle Ⅱ. There are four ways to explore the charmonium-like states at Belle Ⅱ: B meson decays, ISR processes, two-photon collisions, and double charmonium production. Charmonium(-like) states ($X_{c\bar{c}}$) are produced in B meson decays in association with a kaon, $B \to KX_{c\bar{c}}$, which is a Cabibbo–Kobayashi–Maskawa favored process with a relatively large branching fraction of 10^{-4}–10^{-3}.[25] Using an ISR technique, the charmonium-like states with $J^{\rm PC} = 1^{--}$ below e^+e^- center-of-mass (c.m.) energy can be explored and a continuous mass spectrum in a wide region can be studied.[34] The two-photon interaction at Belle Ⅱ via $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X_{c\bar{c}}$ is a typical and effective tool for studying the charmonium-like states with various $J^{\rm P}$ quantum numbers. Double charmonium production, such as $e^+e^- \to J/\psi X_{c\bar{c}}$,[35] provides a good platform for understanding the perturbative and non-perturbative effects in QCD. In the following subsections, we show four promising measurements related to charmonium-like states at Belle Ⅱ in the near future.

4.1 The Absolute Branching Fraction of $X(3872)$ Decay. Measurement of the absolute branching fraction of $X(3872)$ decay can provide key information for identifying the nature of $X(3872)$. The original tetraquark model predicted the branching fraction of $X(3872) \to \pi^+\pi^- J/\psi$ to be about 50%.[36] By contrast, various molecular models predicted this branching fraction to be $\leq 10\%$.[37–41]

Measurement of absolute branching fractions for $X(3872)$ via $B \to KX(3872)$ is unique to B factories. By exclusively reconstructing one B meson ($B_{\rm tag}$) and identifying the K in the decay of the other B meson, the missing mass technique can be used to identify $X(3872)$. Then one can obtain the branching fraction for $B \to KX(3872)$, and further calculate the absolute branching fractions of $X(3872)$ decaying into different final states. No significant $X(3872)$ signal was observed in the recoil mass distribution of K at Belle.[42] Evidence has been found by the BaBar Collaboration for the decay $B \to KX(3872)$ at a 3σ level by allowing all B combinations in an event and performing two layers of neural networks to suppress backgrounds.[43] The branching fraction of $B^+ \to K^+X(3872)$ was measured for the first time to be $(2.1 \pm 0.8) \times 10^{-4}$. In addition, the branching fraction of $X(3872) \to \pi^+\pi^- J/\psi$ was calculated to be $(4.1 \pm 1.3)\%$.

Two improvements have been achieved at Belle Ⅱ: (1) An upgraded Full Event Interpretation (an exclusive reconstruction algorithm)[25] is used to reconstruct thousands of final states for $B_{\rm tag}$ candidates to increase the efficiency. (2) A unique multiple variable analysis of DeepSets based on the neural network[44] is applied to suppress continuum backgrounds and reject the secondary kaons produced in B-daughter D meson decays. The above method may reject about 95% of backgrounds in the $X(3872)$ signal region (81% at BaBar[43]). We expect about 600 $X(3872)$ candidates from the $B \to KX(3872)$ decays per 1 ab^{-1} to be observed at Belle Ⅱ. Therefore, measurements of absolute branching fractions of $X(3872)$ at Belle Ⅱ with much larger data samples in the near future are promising. Surely, the measurements of absolute branching fractions

for other charmonium(-like) states will also be feasible at Belle Ⅱ.

4.2 Search for New Y States in $e^+e^- \to K^+K^-J/\psi$ via ISR. The Y states with specific quantum number $J^{PC} = 1^{--}$ always attract much attention among charmonium-like states. The cross sections for $e^+e^- \to K^+K^-J/\psi$ [$\sigma(e^+e^- \to K^+K^-J/\psi)$] were measured via ISR using the full Belle data, as shown by the dots with error bars in Fig. 3.[45] From Fig. 3, there seems to be abundant structures, although the statistics is limited. Recently, BESⅢ studied the cross sections for $e^+e^- \to K^+K^-J/\psi$ and $e^+e^- \to K^0_SK^0_SJ/\psi$, and found the $Y(4220)$, $Y(4500)$ and $Y(4710)$ states.[46,47] To describe the energy dependency of $\sigma(e^+e^- \to K^+K^-J/\psi)$ in Fig. 3, we include the $Y(4220)$, $Y(4500)$ and $Y(4710)$ components with their masses and widths fixed according to Refs. [46,47], as shown by the blue, black and red dashed curves in Fig. 3. In addition, an extra resonance around 5 GeV, called $Y(5000)$, needs to be included to coincide the higher side of the $\sigma(e^+e^- \to K^+K^-J/\psi)$ distribution. At Belle Ⅱ with much larger data samples, one should measure $Y(4220)$, $Y(4500)$, $Y(4710)$ decaying into K^+K^-J/ψ with higher precision and verify whether there are new resonances with higher masses.

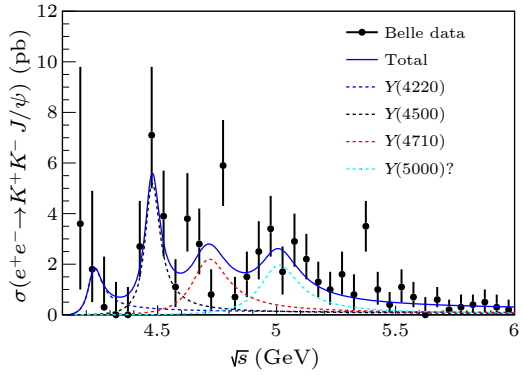

Fig. 3. The measured $e^+e^- \to K^+K^-J/\psi$ cross sections by Belle (dots with error bars).[45] The $Y(4220)$, $Y(4500)$, $Y(4710)$ and $Y(5000)$ components are indicated with dashed curves.

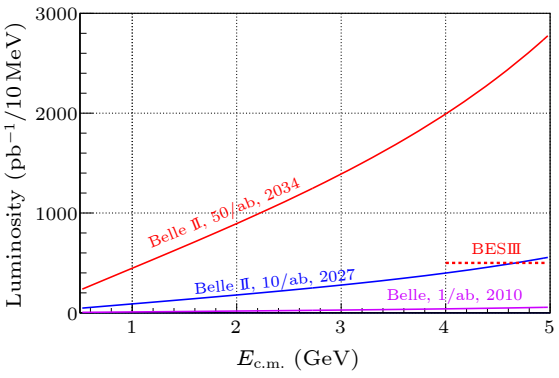

Fig. 4. The effective integrated luminosities at BESⅢ, Belle and Belle Ⅱ.

In the ISR process, the effective integrated luminosity decreases as the c.m. energy decreases, as indicated in Fig. 4. The detection efficiency is also smaller than that in direct e^+e^- annihilations at BESⅢ. However, Belle Ⅱ can provide a continuous mass spectrum instead of a point-by-point one, which helps extract the mass and width for the charmonium-like state precisely. At Belle Ⅱ, one can focus on the higher mass region to search for possible Y states decaying into $K\bar{D}_s^{(*)}D^{(*)}$, $\bar{D}_s^{(*)}D_{s1}(2460)$, $\bar{D}_s^{(*)}D_{s1}(2536)$, $\bar{D}_s^{(*)}D^*_{s2}(2573)$, $\bar{D}^*_sD^*_{s0}(2317)$, $\bar{\Lambda}_c\Lambda_c$, $\bar{\Lambda}_c\Sigma_c$, $\bar{\Sigma}_c\Sigma_c$, $\bar{\Xi}_c\Xi_c$, etc. The intermediate states $Z_{cs} \to KJ/\psi$ and $Z_{cs} \to \bar{D}_s^{(*)}D^{(*)}$ can be also searched for in the above processes.

4.3 Confirmation of $X(4350)$ and Determination of J^P for $X(3915)$ in Two-Photon Collisions. $X(4140) \to \phi J/\psi$ was first reported by CDF in $B^+ \to K^+\phi J/\psi$.[48,49] Then, Belle and BaBar searched for such a state in the same B decay, but did not confirm its presence.[50,51] CMS, D0, and LHCb also searched for $X(4140)$, and found its signal to be significantly larger than 3σ (D0[52]) or 5σ (CMS and LHCb[53,54]). In the full amplitude analysis from LHCb, $X(4140)$, $X(4274)$, $X(4500)$, and $X(4700)$ were observed.[54] The structures in the $\phi J/\psi$ mass spectrum seem to be very rich. Therefore, it is worth studying the $\phi J/\psi$ mass spectrum in other processes.

The $\gamma\gamma \to \phi J/\psi$ process was measured between the threshold to 5 GeV/c^2 using a data sample of 825 fb^{-1} at Belle.[55] A narrow peak was observed around 4.530 GeV, named as $X(4350)$. The signal yield is $8.8^{+4.2}_{-3.2}$ with a significance of 3.2σ including systematic uncertainty. This state has not yet been confirmed by other experiments. It should be noted that the production of $X(4140)$ and $X(4274)$ with $J^P = 1^+$ observed by LHCb[54] in two-photon fusions is forbidden according to the Landau–Yang theorem. When the data collected at Belle Ⅱ reach 1 ab^{-1}, together with all of the Belle data, the significance of $X(4350)$ is expected to exceed 5σ as an observation.

$X(3915)$ was originally seen by Belle in its $\omega J/\psi$ decay mode and was produced in both B decays and two-photon collisions.[56,57] The mass and width of $X(3915)$ in $\gamma\gamma \to \omega J/\psi$ were measured to be (3915 ± 4) MeV/c^2 and (17 ± 11) MeV.[57] Subsequently, BaBar confirmed its existence and supported the assignment $J^P = 0^+$ based on a spin-parity analysis, thus identifying $X(3915)$ as a $\chi_{c0}(2P)$ state.[58] However, the properties of $X(3915)$ do not fit expectations for $\chi_{c0}(2P)$ since it has a mass 190 MeV/c^2 above the s-wave $D\bar{D}$ threshold but only has a width of 20 MeV.[59,60] Moreover, in Ref. [61], the authors proposed that the spin-parity of $X(3915)$ should be 2^{++} if the $X(3915)$ has a non-$c\bar{c}$ admixture. Recently, LHCb performed an amplitude analysis of the $B^+ \to D^+D^-K^+$ decay and found a new spin-0 charmonium resonance around 3.92 GeV/c^2.[62] If it is the same state as observed in the $\omega J/\psi$ decay, $X(3915)$ can be regarded as a $\chi_{c0}(2P)$ state. To figure out this long-term unsolved issue concerning the J^P of $X(3915)$, the angular distribution in $\gamma\gamma \to \omega J/\psi$ at Belle Ⅱ with high precision can provide effective experimental information.

5. Prospects for Bottomonium-Like States at Belle Ⅱ. There are at least four ways to explore the bottomonium-

like states at Belle Ⅱ: direct e^+e^- annihilations, ISR processes, hadronic transitions, and radiative transitions. In e^+e^- collisions, the c.m. energy can be set at some specific energy points to precisely measure the masses and widths of known resonances, and search for possible new states. $\Upsilon(10753)$ was discovered using direct e^+e^- collision data and the ISR process from 10.52 to 11.02 GeV at Belle.[63] The hadronic and radiative transitions are effective ways to search for new bottomonium-like states. Noticeably, $h_b(1P)$ and $h_b(2P)$ were observed in the $\pi^+\pi^-$ transitions from $\Upsilon(10860)$ at Belle;[27,64] $Z_c(10610)$ and $Z_c(10650)$ were observed in the pion transitions from $\Upsilon(10860)$ and $\Upsilon(11020)$ at Belle;[12,26,27,29] $\eta_b(2S)$ was evident via the radiative decay of $h_b(2P)$ in $e^+e^- \to \Upsilon(5S) \to h_b(2P)(\to \gamma\eta_b(2S))\pi^+\pi^-$ at Belle.[65]

5.1 Research of $\Upsilon(10753)$. $\Upsilon(10753)$ was first observed by Belle in the energy dependence of cross sections for $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$ with a significance of 5.2σ including systematic uncertainties.[63] The mass and width of $\Upsilon(10753)$ are $(10752.7^{+5.9}_{-6.0})\,\mathrm{MeV}/c^2$ and $(35.5^{+18.0}_{-11.8})\,\mathrm{MeV}$. Its existence is further supported by a fit to the 'dressed' cross sections $\sigma(e^+e^- \to b\bar{b})$ at c.m. energies $\sqrt{s}$ from 10.6 to 11.2 GeV.[66] $\Upsilon(10753)$ was interpreted as a conventional bottomonium,[67–76] hybrid[3,77] or tetraquark state.[78–82] The nature of $\Upsilon(10753)$ has not yet been identified.

To further understand the nature of $\Upsilon(10753)$, Belle Ⅱ collected $19\,\mathrm{fb}^{-1}$ of unique data at four energy points around 10.75 GeV in November 2021. Using these data, measurement of $e^+e^- \to \omega\chi_{bJ}(1P)$ $(J = 0, 1, 2)$ was performed.[83] The Born cross sections of $e^+e^- \to \omega\chi_{b1,b2}(1P)$ as a function of $\sqrt{s}$ are shown in Fig. 5, where the $\Upsilon(10753) \to \omega\chi_{b1,b2}(1P)$ signal is clear. The Born cross section ratio between $e^+e^- \to \omega\chi_{b1,b2}(1P)$ and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$ is about 1.5 at $\sqrt{s} = 10.745$ GeV and 0.15 at $\sqrt{s} = 10.867$ GeV.[83,84] This indicates different internal structures for $\Upsilon(10753)$ and $\Upsilon(10860)$, which otherwise have the same quantum numbers and are only $110\,\mathrm{MeV}/c^2$ apart.

Using the above-mentioned data samples, $e^+e^- \to B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$ signals at $\sqrt{s} = 10.653$, 10.701, 10.745, and 10.805 GeV were observed.[85] By combining the Belle results at $\sqrt{s}$ from 10.63 to 11.02 GeV[86] and Belle Ⅱ results at the above-mentioned four energy points,[85] the energy dependences of cross sections for $e^+e^- \to B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$ were obtained. A new and unexpected observation is that the $e^+e^- \to B^*\bar{B}^*$ cross section increases rapidly just above the threshold, which can be explained by presence of a resonance or a bound state of $B^*\bar{B}^*$ near the $B^*\bar{B}^*$ threshold.[87,88] Using the above-mentioned data samples, $\eta_b(1S)$ and $\chi_{b0}(1P)$ were searched for in the ω recoil mass distribution. No significant signals were observed, and upper limits at a 90% credibility level on the Born cross sections were set to be 2.5 pb and 8.6 pb for $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$ at $\sqrt{s} = 10.745$ GeV, respectively.[85]

More analyses are ongoing, including the searches for $e^+e^- \to \gamma X_b$ [X_b is the bottom partner of $X(3872)$], $\Upsilon(10753) \to \eta\Upsilon(nS)$ $(n = 1, 2, 3)$, $\Upsilon(10753) \to K^+K^-\Upsilon(1S)$, and $\Upsilon(10753) \to \gamma\chi_{bJ}(1P)$, etc. These measurements help us understand the internal structure of $\Upsilon(10753)$, and enrich our knowledge of bottomonium spectroscopy.

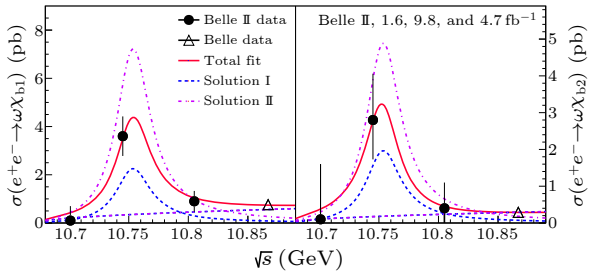

Fig. 5. The Born cross sections of (left) $e^+e^- \to \omega\chi_{b1}(1P)$ and (right) $e^+e^- \to \omega\chi_{b2}(1P)$ as a function of $\sqrt{s}$.[83] The red solid curves show the total fits. The dashed curves show two solution results.

5.2 Bottomonium-Like States above the $B\bar{B}$ *Mass Threshold.* Below the $B\bar{B}$ threshold, bottomonia are described well by the potential models in QCD.[89–91] Above the $B\bar{B}$ threshold, bottomonia demonstrate the following unexpected properties. There is no position for $Z_b(10610)$ and $Z_b(10650)$ in the bottomonium potential model. In comparison with charmonium-like states, the number of observed bottomonium-like states is much smaller.[25] The decay $\Upsilon(4S) \to \eta h_b(1P)$, forbidden in Heavy Quark Effective Theory,[92,93] has a larger probability than that of $\pi^+\pi^-\Upsilon(nS)$ $(n = 1, 2, 3)$.[94] For $\Upsilon(5S)$ and $\Upsilon(6S)$, their widths to $\pi^+\pi^-\Upsilon(nS)$ and $K^+K^-\Upsilon(nS)$ are several orders of magnitude larger than those of $\Upsilon(4S)$.[95] At this point, there is not enough experimental information for a systematic solution to this problem in the case of bottomonia. The relevant measurements with data collected in the bottomonium energy region at Belle Ⅱ will provide additional information.

At Belle Ⅱ, an energy scan from the $B\bar{B}$ threshold up to the highest possible energy of 11.24 GeV with $\sim 10\,\mathrm{fb}^{-1}$ per point and ~ 10 MeV step is of great interest in the search for new excited Υ and Y_b (bottomonium-like states with $J^{\mathrm{PC}} = 1^{--}$) states.[33] If the new bottomonium(-like) states are observed, about $500\,\mathrm{fb}^{-1}$ data will be collected at corresponding energy points to perform a detailed study of radiative and hadronic transitions and to search for X_b and other Z_b states. Unlike $X(3872)$ decays, due to negligible isospin-breaking effects X_b may decay preferentially into $\pi^+\pi^-\pi^0\Upsilon(nS)$, $\pi^+\pi^-\chi_{bJ}(1P)$ and $\gamma\Upsilon(nS)$, instead of $\pi^+\pi^-\Upsilon(1S)$.[96–99] Although open flavor channels dominate the Z_b decays, one can still search for more Z_b states in $\pi\Upsilon(nS)$, $\pi h_b(nP)$ and $\rho\eta_b(nS)$ systems due to a higher reconstruction efficiency and free continuum contribution.[100,101] Combined coupled-channel analyses of all exclusive cross sections will allow us to determine the pole positions of the $\Upsilon(nS)$ and Y_b states, their electronic widths and couplings to various channels. Increase in the maximal energy of 11.24 GeV by at least 100 MeV will allow us to explore the $\Lambda_b^0\bar{\Lambda}_b^0$ threshold and to search

for baryon–antibaryon molecular states.[33] In the Λ_b^0 decays, the exotic baryons P_c could be investigated at Belle Ⅱ.

6. Summary. Belle has made great achievements in the field of exotic hadrons. The experimental studies at Belle Ⅱ will proceed along the same lines as at Belle. Measurements of absolute branching fractions for $X_{c\bar{c}}$ via $B \to K X_{c\bar{c}}$ are unique to Belle Ⅱ with an advanced multiple variable analysis based on the neural network. Besides B decays, the ISR technique, two-photon collisions and double charmonium production are also effective tools for exploring charmonium-like states. Belle Ⅱ will collect abundant data around $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances, providing an ideal platform for studying the bottomonium-like states above the $B\bar{B}$ threshold. The Y_b, X_b and Z_b states can be widely investigated using these data in the near future.

Acknowledgments. This work was supported by the National Natural Science Foundation of China (Grant Nos. 12342024, 12135005, 12135005, 11975076, and 12005040), and the Fundamental Research Funds for the Central Universities (Grant No. RF1028623046).

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