SUMMARY OF THE RESULTS ON SPECTROSCOPY FROM BELLE*

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We present the recent results on the hadron spectroscopy measured by the Belle detector at the KEKB e^+e^- collider. We picked up the bottomonium-like and charmonium-like mesons having the unanticipated properties from the $q\bar{q}$ structures as well as the recently observed $h_b(1,2P)$ mesons.

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1. Introduction

The Belle experiment ran at the KEKB [1] e^+e^- asymmetric energy collider between 1999 and 2010 and the total integrated luminosity reached 1040 fb^{-1}. Most of the data were taken at the energy of the $\Upsilon(4S)$ resonance in order to study the B physics, but also other energy data were taken, as listed in Table I. The physics events were detected by the general purpose Belle spectrometer [2], which consists of a silicon vertex detector, a central drift chamber, an array of aerogel Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters and an electromagnetic calorimeter. Arrays of resistive plate counters interspersed in the iron yoke is used for the identification of muons and $K_{\rm L}$ mesons. The physics achievements from the Belle experiment until 2012 are reviewed in Ref. [3].

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TABLE I

Summary of the luminosity of the Belle experiment. "On-peak" means the energy is just at the resonance points and "off-peak" means the energy is 60 MeV below the resonance points. "Scan" means the energy is scanned between the $\Upsilon(4S)$ and $\Upsilon(6S)$ resonances.

Resonance	On-peak luminosity [fb^{-1}]	Off-peak luminosity [fb^{-1}]	Number of resonances
$\Upsilon(1S)$	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	772×10^6
$\Upsilon(5S)$	121.4	1.7	7.1×10^6
Scan		27.6	

2. Bottomonium-like hadrons

2.1. Anomalous $\Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ production near $\Upsilon(5S)$ resonance

The $\Upsilon(10860)$ resonance is the $J^{PC} = 1^{--}$ state with the mass of 10876 ± 11 MeV and the width of 55 ± 28 MeV. The main component of this resonance is considered as the 5$^{\text{th}}$ excited state of the orbital angular moment $L = 0$ bottomonium, and therefore, sometimes called $\Upsilon(5S)$. Its mass is above the open bottom threshold and the decays to $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$ and $B_s\bar{B}_s$ have been observed. In 2008, Belle reported the first observation of $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$ and the first evidence for $e^+e^- \to \Upsilon(3S)\pi^+\pi^-$, $\Upsilon(1S)K^+K^-$ near the peak of the $\Upsilon(5S)$ resonance at $\sqrt{s} \sim 10.87$ GeV [4]. The $\Upsilon(nS)$ was detected through the $\Upsilon(nS) \to \mu^+\mu^-$ decay mode. Signal candidates were identified using the kinematic variable ΔM, defined as the difference between $M(\mu^+\mu^-\pi^+\pi^-)$ or $M(\mu^+\mu^-K^+K^-)$ and $M(\mu^+\mu^-)$ for pion or kaon modes. The signal events should be concentrated at $\Delta M = \sqrt{s} - M_{\Upsilon(nS)}$ and results are given in Fig. 1. By analyzing the data and assuming the $\Upsilon(5S)$ to be the sole source of the observed events, the partial decay widths have been obtained. The results are summarized in Table II. The measured partial widths, of the order of 0.6–0.9 MeV, are more than 2 orders of magnitude larger than the corresponding partial widths for $\Upsilon(4S)$, $\Upsilon(3S)$ or $\Upsilon(2S)$ decays. The unexpectedly large partial widths disagree with the expectation for a pure $b\bar{b}$ state, and therefore, the $\Upsilon(5S)$ is one of the strong candidates for the unquenched hadron.

In order to understand the nature of the $\Upsilon(5S)$ state, Belle measured the production cross sections for $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$ and $\Upsilon(3S)\pi^+\pi^-$ as a function of $\sqrt{s}$ between 10.83 GeV and 11.02 GeV [5]. The enhancements of the production cross sections were observed in all

three final states. A fit using a Breit–Wigner resonance shape yields a peak mass of $[10888.4^{+2.7}_{-2.6}(\text{stat}) \pm 1.2(\text{syst})]$ MeV/c^2 and a width of $[30.7^{+8.3}_{-7.0}(\text{stat}) \pm 3.1(\text{syst})]$ MeV/c^2. The peak mass obtained here is about 12 MeV above the PDG average mass.

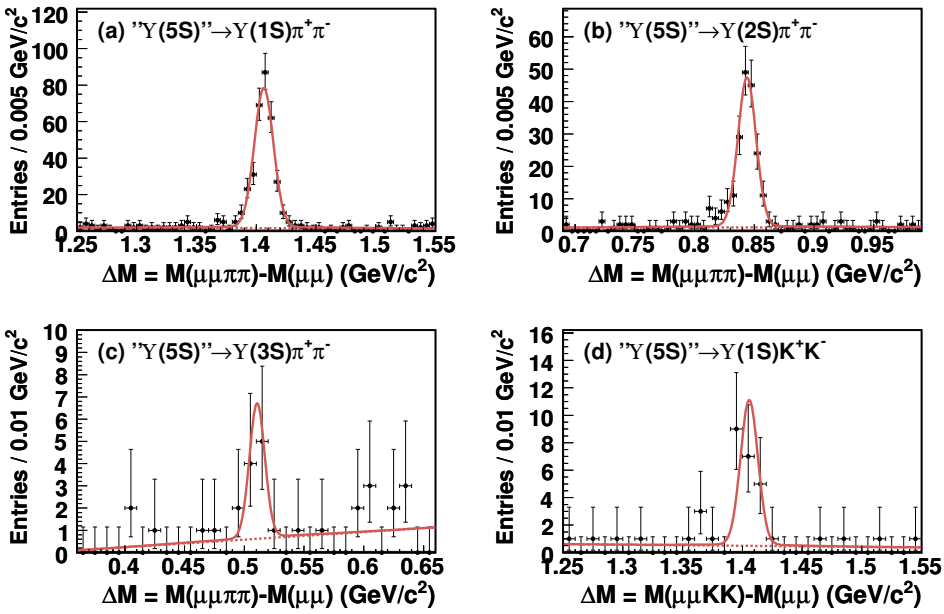


Fig. 1. The ΔM distributions for (a) $\Upsilon(1S)\pi^+\pi^-$, (b) $\Upsilon(2S)\pi^+\pi^-$, (c) $\Upsilon(3S)\pi^+\pi^-$, and (d) $\Upsilon(1S)K^+K^-$ with the fit results superimposed. The dashed curves show the background components in the fits. Figures are taken from Ref. [4].

TABLE II

Signal yield (N_s), significance (Σ) and the partial widths (Γ) for $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$ are also given. The first uncertainty is statistical, and the second is systematic.

Process	N_s	Σ	Γ [MeV]
$\Upsilon(1S)\pi^+\pi^-$	325^{+20}_{-19}	20σ	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	186 ± 15	14σ	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$10.5^{+4.0}_{-3.3}$	3.2σ	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$20.2^{+5.2}_{-4.5}$	4.9σ	$0.067^{+0.017}_{-0.015} \pm 0.013$

2.2. First observation of the P-wave spin-singlet bottomonium states

The $h_b(nP)$ states are the P-wave spin-singlet bottomonium. In 2012, Belle reported the first observations of the $h_b(1P)$ and $h_b(2P)$ produced via $e^+e^- \to \pi^+\pi^- h_b(nP)$ using a 121.4 fb^{-1} data sample collected at energies near the $\Upsilon(5S)$ resonance [6]. The $h_b(nP)$ states were observed in the $\pi^+\pi^-$ missing mass spectrum defined as $M^2_{\rm miss} \equiv (P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2$, where $P_{\Upsilon(5S)}$ is the 4-momentum of the $\Upsilon(5S)$ determined from the beam momenta and $P_{\pi^+\pi^-}$ is the 4-momentum of the $\pi^+\pi^-$ system. The $M_{\rm miss}$ spectrum is divided into three adjacent regions with boundaries at $M_{\rm miss} = 9.3$, 9.8, 10.1, and 10.45 GeV/c^2 and fitted separately in each region. In the third region, prior to fitting, the contribution due to the $K^0_{\rm S} \to \pi^+\pi^-$ is subtracted. In Fig. 2, the $M_{\rm miss}$ spectrum after subtraction of both the combinatoric and $K^0_{\rm S} \to \pi^+\pi^-$ contributions is shown with the fitted signal functions. The measured masses of $h_b(1P)$ and $h_b(2P)$ are $M = (9898.2^{+1.1+1.0}_{-1.0-1.1})$ MeV/c^2 and $M = (10259.8 \pm 0.6^{+1.4}_{-1.0})$ MeV/c^2, respectively. Using the world average masses of the $\chi_{bJ}(nP)$ states, the P-wave hyperfine splittings are determined to be $\Delta M_{\rm HF} = (+1.7 \pm 1.5)$ and $(+0.5^{+1.6}_{-1.2})$ MeV/c^2, respectively. The significances of the $h_b(1P)$ and $h_b(2P)$ are 5.5σ and 11.2σ, respectively.

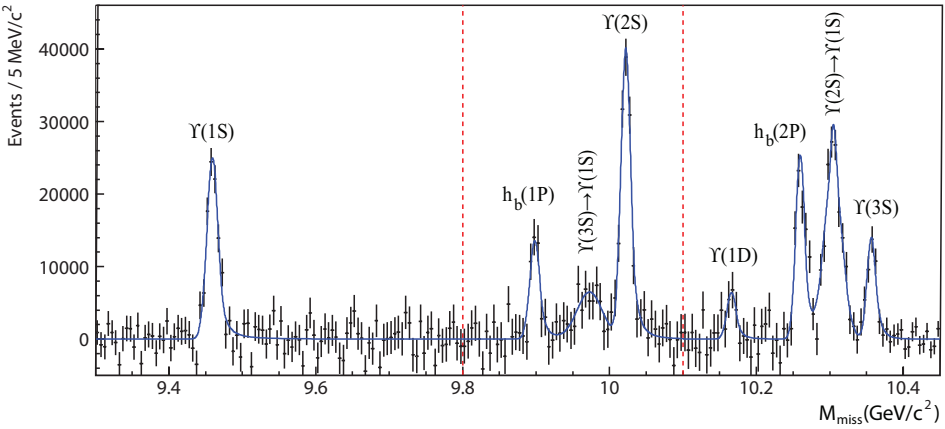


Fig. 2. The $M_{\rm miss}$ spectrum with the combinatoric background and $K^0_{\rm S}$ contribution subtracted (points with errors) and signal component of the fit function overlaid (smooth curve). The vertical lines indicate boundaries of the fit regions. Figure is taken from Ref. [6].

2.3. First observation of two charged bottomonium-like resonances; $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$

In 2012, Belle reported the first observations of two narrow charged bottomonium-like resonances in the mass spectra of the $\pi^\pm\Upsilon(nS)$ ($n = 1,2,3$) and $\pi^\pm h_b(mP)$ ($m = 1,2$) pairs that were produced in association with a single charged pion in $\Upsilon(5S)$ decays [7]. Amplitude analyses of the three-body $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ decays were performed by means of unbinned maximum likelihood fits to two-dimensional $M^2[\Upsilon(nS)\pi^+]$ *vs.* $M^2[\Upsilon(nS)\pi^-]$ Dalitz distributions. Two peaks were observed in the $\Upsilon(nS)\pi^\pm$ system near 10.61 GeV/c^2 and 10.65 GeV/c^2. The statistical significance of the two peaks exceeded 10σ for all $\Upsilon(nS)\pi^+\pi^-$ channels. Similarly, two peaks were observed in the $h_b(mP)\pi^\pm$ system. The significance of the $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ is 16.0σ [5.6σ] for the $h_b(1P)$ [$h_b(1P)$]. Weighted averages of the mass and width are $M = 10607.2 \pm 2.0$ MeV/c^2, $\Gamma = 18.4 \pm 2.4$ MeV for the $Z_b(10610)^\pm$ and $M = 10652.2 \pm 1.5$ MeV/c^2, $\Gamma = 11.5 \pm 2.2$ MeV for the $Z_b(10650)^\pm$, where statistical and systematic errors are added in quadrature. Recent amplitude analysis of the three-body $\Upsilon(nS)\pi^+\pi^-$ final states strongly favored $I^G(J^P) = 1^+(1^+)$ quantum-number assignments [8]. Since the minimal quark content is $b\bar{b}u\bar{d}$ [$b\bar{b}d\bar{u}$] for the Z_b^+ [Z_b^-], the $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ are the genuine exotic hadrons. The measured masses of two states are a few MeV/c^2 above the thresholds for the open bottom channels $B^*\bar{B}$ (10604.46 MeV/c^2) and $B^*\bar{B}^*$ (10650.2 MeV/c^2). This suggests that these states have a hadronic molecular-type structure.

2.4. First observation of $Z_b(10610)^0$

Belle reported the first observation of the neutral partner of the $Z_b(10610)^\pm$, the $Z_b(10610)^0$ decaying to $\Upsilon(2,3S)\pi^0$ with a 6.5σ significance using a Dalitz analysis of $\Upsilon(5S) \to \Upsilon(2,3S)\pi^0\pi^0$ decays [9]. The measured mass of the $Z_b(10610)^0$ is $M = (10609 \pm 4 \pm 4)$ MeV/c^2, that is consistent with the mass of the corresponding charged state, the $Z_b(10610)^\pm$. This suggests that the isospin symmetry breaking is small for $Z_b(10610)$s and an admixture of the $b\bar{b}$ component in $Z_b(10610)^0$ is small.

3. Charmonium-like hadrons

3.1. $Y(4260)$, $Y(4360)$ and $Y(4660)$

The $Y(4260)$ state was first observed by the BaBar Collaboration in the initial-state-radiation (ISR) process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ [10] and then confirmed by the CLEO [11] and Belle experiments [12, 13] using the same technique. The cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ are given in Fig. 3.

The quantum number of the $Y(4260)$ resonances is $J^{PC} = 1^{--}$. However, the properties of the $Y(4260)$ resonance are rather different from those of other known $J^{PC} = 1^{--}$ charmonium states in the same mass range. Since it is well above the $D\bar{D}$ threshold, it is expected to decay into $D^{(*)}\bar{D}^{(*)}$ dominantly. In fact, no significant enhancement is observed in $D^{(*)}\bar{D}^{(*)}$ final states. On the other hand, $\Gamma(Y(4260) \to \pi^+\pi^- J/\psi) > 1.6$ MeV at 90% C.L., which is much larger than the typical charmonium state, *i.e.*, $\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) = 53 \pm 8$ keV.

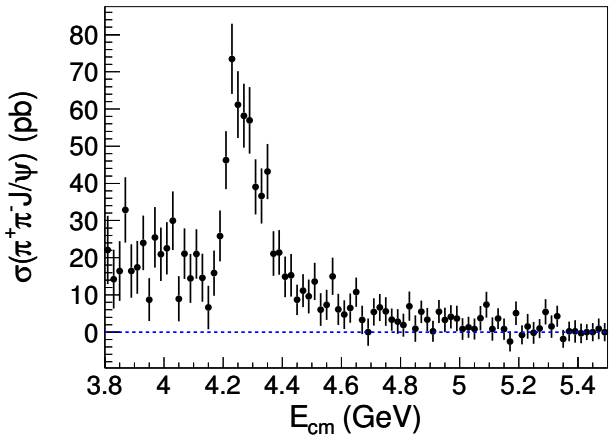


Fig. 3. The measured $e^+e^- \to \pi^+\pi^- J/\psi$ cross section for c.m. energies between 3.8 and 5.5 GeV after background subtraction. The errors are statistical only. Figure is taken from Ref. [13].

In 2007, Belle reported the observation of two resonance structures in $e^+e^- \to \pi^+\pi^-\psi(2S)$ via initial-state radiation [14]. The masses and widths of the two resonances ($Y(4360)$ and $Y(4660)$) are $M_1 = 4361 \pm 9 \pm 9$ MeV/c^2, $\Gamma_1 = 74 \pm 15 \pm 10$ MeV and $M_2 = 4664 \pm 11 \pm 5$ MeV/c^2, $\Gamma_2 = 48 \pm 15 \pm 3$ MeV, respectively, if the mass spectrum is parametrized with the coherent sum of two Breit–Wigner functions. The statistical significance of the first peak is more than 8σ and that of the second peak is 5.8σ. The measured cross sections are given in Fig. 4. Likewise, $Y(4260)$, $Y(4360)$ and $Y(4660)$ are not observed in $D^{(*)}\bar{D}^{(*)}$ channels. $Y(4260)$ has rather large partial decay width to the $\pi^+\pi^- J/\psi$ final state, but has quite small partial decay width to the $\pi^+\pi^-\psi(2S)$ final state. Conversely, $Y(4360)$ and $Y(4660)$ have large partial decay width to the $\pi^+\pi^-\psi(2S)$ final state, but have small partial decay width to the $\pi^+\pi^- J/\psi$ final state. These facts suggest that $Y(4260)$, $Y(4360)$ and $Y(4660)$ are not simple charmonium states, and therefore, are the candidates for the unquenched hadrons.

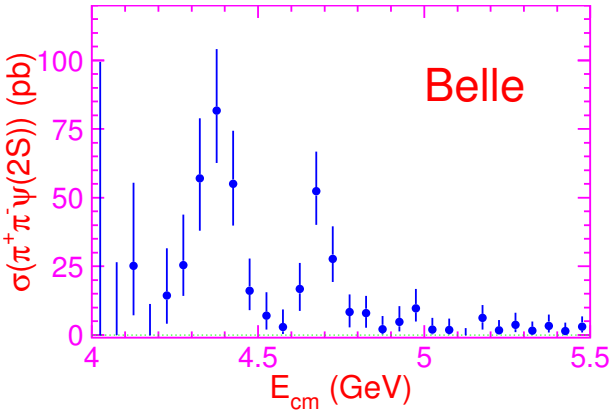


Fig. 4. The measured $e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section for c.m. energies between 4.0 and 5.5 GeV after background subtraction. The errors are statistical only. Bins without entries have a central value of zero. Figure is taken from Ref. [14].

3.2. $Z_c(3900)$

The $J^{PC} = 1^{--}$ state $Y(4260)$ has rather large decay width to the $\pi^+\pi^- J/\psi$ and it is similar to the $J^{PC} = 1^{--}$ state $\Upsilon(10860)$ that has rather large decay width to the $\pi^+\pi^-\Upsilon(1S)$. In the $\Upsilon(10860)$ decay, the charged bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ were observed as described in Sect. 2.3. Likewise $\Upsilon(10860)$, whether the $Y(4260)$ decay to the charged charmonium-like state was the issue of the discussion. Recently, BESIII reported [15], and Belle confirmed [13], the observation of a charged resonance-like structure in the $\pi^+ J/\psi$ invariant mass distribution for $e^+e^- \to \pi^+\pi^- J/\psi$ events collected at $\sqrt{s} = 4.26$ GeV, dubbed the $Z_c(3900)$. The mass and width determined by BESIII are $M = (3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and $\Gamma = (46 \pm 10 \pm 20)$ MeV, respectively with more than 8σ statistical significance. Those by Belle are $M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2 and $\Gamma = (63 \pm 24 \pm 26)$ MeV, respectively with 5.2σ significance. The fit results of the distribution of $M_{\rm max}(\pi J/\psi)$, the maximum of $M(\pi^+ J/\psi)$ and $M(\pi^- J/\psi)$ by Belle are given in Fig. 5. Recently, BESIII reported on a study of the process $e^+e^- \to \pi^\pm (D\bar{D}^*)^\mp$ at $\sqrt{s} = 4.26$ GeV using a 525 pb^{-1} data sample collected with the BESIII detector at BEPCII storage ring. A distinct charged structure dubbed $Z_c(3885)$ is observed with more than 18σ significance [16]. The measured mass and width are $M = (3883.9 \pm 1.5 \pm 4.2)$ MeV/c^2 and $\Gamma = (24.8 \pm 3.3 \pm 11.0)$ MeV, respectively. The fitted $Z_c(3885)$ mass is marginally (2σ) inconsistent with that of the $Z_c(3900)$, and therefore, it is an issue of the discussion whether the $Z_c(3885)$ structure is identical with the $Z_c(3900)$ structure.

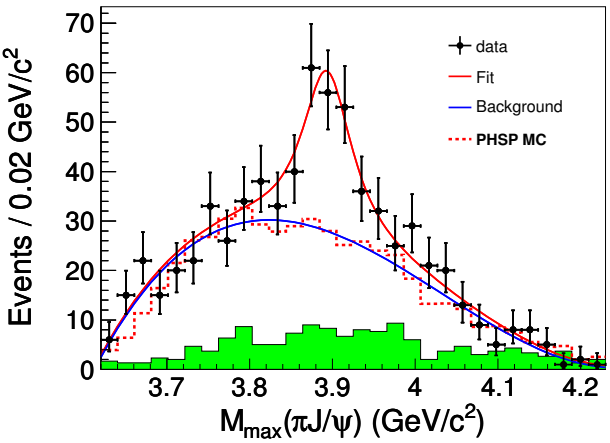


Fig. 5. Unbinned maximum likelihood fit to the distribution of the $M_{\max}(\pi J/\psi)$. Points with error bars are data, the curves are the best fit, the dashed histogram is the phase space distribution and the shaded histogram is the non-$\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands. Figure is taken from Ref. [13].

Since the mass of $Z_c(3885)$ or $Z_c(3900)$ is close to the $D^0\bar{D}^{*-}$ threshold, there are suggestions that these states are the virtual $D\bar{D}^*$ molecule-like structure, *i.e.*, a charmed-sector analog of the $Z_b(10610)$. However, the situation is not so simple. Because of the heavy quark symmetry, the interaction between $B^{(*)}$ and $\bar{B}^{(*)}$ is considered to be similar to that between $D^{(*)}$ and $\bar{D}^{(*)}$. On the other hand, the size of the kinetic energy term of the $D\bar{D}^*$ system is about 2.7 times larger than that of the $B\bar{B}^*$ system due to the reduced mass difference. Therefore, simultaneous explanation of the $Z_b(10610)$ and $Z_c(3900)$ structures are rather difficult.

4. Summary

The recent results on the hadron spectroscopy measured by the Belle detector at the KEKB e^+e^- collider have been reviewed. We have focused on the bottomonium-like and charmonium-like mesons having the unanticipated properties from the $q\bar{q}$ structures.

Although the data taking of the Belle experiment was finished on June 30, 2010, there may be rich hadron physics to be analyzed in Belle data. Quantum numbers, production rates, decay rates, *etc.* have not been determined for many higher resonance states, which should be measured. As discussed in this paper, many states may not have the simple quark–gluon structures

but have the rich (unquenched) structures. In order to clarify the structures of such exotic (unquenched) hadrons, any suggestion from the theorists is very welcome.

The Super KEK B-factory/Belle II experiment will start data taking in 2017. The designed luminosity is 40 times bigger than the KEK B-factory/ Belle. Please await our new data from the Super KEK B-factory/Belle II.

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