New and conventional bottomonium states

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Recent progress on the bottomonium states is reported. This talk briefly reviews the observation of \( h_b(1P), h_b(2P), Z_{b1}^+, Z_{b2}^+ \) states, transition of \( h_b(nP) \rightarrow \eta_b(mS)\gamma \) and new studies on the \( \eta_b(2S) \) state. Other \( \eta \) and \( \pi^+\pi^- \) transitions of \( \Upsilon(nS) \) are also discussed.

I. STUDY OF BOTTOMONIUM

The history of bottomonium starts in mid 1977 where an enhancement was observed at a \( \mu^+\mu^- \) mass peak near 9.5 GeV, from the collision of 400 GeV protons on nuclear targets at Fermilab [1]. In 1978, with much improved resolution, the \( \Upsilon \) particle was observed with a width limited by energy spread of beams at the DORIS \( e^+e^- \) storage ring. Just like the \( J/\psi \) particle, the \( \Upsilon \) discovery comes from direct production, thanks for the spin-parity \( J^P = 1^- \) and its substantial leptonic partial width.

However, other particles of the bottomonium family can not be directly produced at an \( e^+e^- \) collider. So, alternative experimental methods should be used to search for these states. For example, the \( P \)-wave states of \( b \) and \( \bar{b} \) were discovered using the inclusive photon spectrum of \( \Upsilon' \) decay at Crystal Ball collaboration in 1985. In Fig. 1(left), A triplet of peaks between 100 and at 200 MeV is clearly seen, which corresponds to \( \Upsilon' \rightarrow \gamma\chi_b(3P_{2,1,0}) \) transitions, while the peak at the right is due to reflection from \( \chi_b \rightarrow \gamma\Upsilon \).

Now, a large of set bottomonium states has been predicted and studied, which was nicely arranged according to the \( b\bar{b} \) level scheme (PDG). Recent discoveries of new bottomonium states also follow the history, where the inclusive or semi-inclusive methods play important role. As two examples not long ago, BaBar collaboration discovered the lowest lying bottomonium state \( \eta_b \) using the same inclusive \( \gamma \) spectrum method [3], and CLEO collaboration discovered...
\(\Upsilon(1D)\) using the recoil mass of two soft \(\gamma\)s with \(l^+l^-\) tagging \([3]\), which represents the inclusive property of two \(\gamma\)s. In the following sections, recent results of bottomonium, especially those obtained from Belle’s large 121.4 fb\(^{-1}\) \(\Upsilon(5S)\) data, are discussed.

II. \(\Upsilon(5S)\) AND \(h_b\) PARTICLES

In 2008, Belle collaboration reported surprising large partial widths of \(\Upsilon(5S) \rightarrow \Upsilon(1,2,3S)\pi^+\pi^-\) \([5]\), which are two orders of magnitude larger than the widths of \(\Upsilon(2,3,4S) \rightarrow \Upsilon(1S)\pi^+\pi^-\). While the reason of this discrepancy is unclear, an \(\Upsilon\) state different from the conventional \(b\bar{b}\) bound state has been considered \([6]\).

In 2011, CLEO-c collaboration suggested that the cross-sections of \(h_c\pi^+\pi^-\) and \(J/\psi\pi^+\pi^-\) are of similar magnitude, and are all enhanced near 4.26 GeV \(e^+e^-\) energy \([7]\), although for \(h_c\pi^+\pi^-\) the statistics was limited. Interpreting this enhancement as the \(Y(4260)\) resonance, the partial width of \(Y(4260) \rightarrow J/\psi\pi^+\pi^-\) has been shown to be greater than 508 keV at 90\% confidence level \([8]\), which is much larger than the partial widths of \(\psi'\) (102 keV) and \(\psi''\) (53 keV). This behavior is similar to the bottomonium case of \(\Upsilon(5S)\). Thus, we naturally think that the \(h_b\pi^+\pi^-\) production rate is also greatly enhanced in the \(\Upsilon(5S)\) region, by assuming the similar mechanism as in the charmonium case.

The \(h_b\) decay modes are unknown and should be complicated, since it will decay to light quarks. In order to study the decay \(\Upsilon(5S) \rightarrow h_b\pi^+\pi^-\), we can still use inclusive method to avoid reconstructing \(h_b\) directly. The recoil or missing mass of \(\pi^+\pi^-\) defined as \(MM(\pi^+\pi^-) = \sqrt{(P(\Upsilon(5S)) - P(\pi^+\pi^-))^2}\) was studied at Belle. Here \(P\) is the four momentum of relevant particles, with the \(P(\Upsilon(5S))\) obtained from beam energies. The spectrum of \(MM(\pi^+\pi^-)\) shown in Fig. 1 is of huge statistics which is around 1 million events per 1 MeV. Nevertheless, it shows the similar behavior compared to the Crystal Ball’s inclusive photon plot in Fig. 1 left. By fitting it, Belle made the first observation of \(h_b(1P)\) and \(h_b(2P)\) states \([9]\), whose masses agree with the theoretical expectation from center-of-gravity of \(\chi_b\) states. However, the mechanism of \(\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-\) decay is exotic, because the ratio of spin-flip to non-spin-flip branching fractions \(\Gamma(\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-)/\Gamma(\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-)\) are not suppressed.

III. \(Z_b\) PARTICLES

While CLEO-c did not report any resonance structure in the \(h_c\pi^+\pi^-\) system, Belle has enough statistics to study the resonance structure of the three body \(h_b\pi^+\pi^-\) in \(\Upsilon(5S)\) decay. This was achieved by looking the missing mass of a single \(\pi^+\) or \(\pi^-\), which should effectively be the \(M(h_b\pi^-)\) or \(M(h_b\pi^+)\). Because of symmetry transposing \(\pi^+\) and \(\pi^-\), the two missing mass distributions is combined and upper half of the available range is used, which we denote as \(MM(\pi)\) distribution. Then the missing mass of two pions \(MM(\pi^+\pi^-)\) was fitted to extract \(h_b(1P)\) and \(h_b(2P)\) signals in bins of \(MM(\pi)\). The resulting spectra of \(h_b\) yields as a function \(MM(\pi)\) will be background-free distributions for \(M(h_b(1P)\pi)\) and \(M(h_b(2P)\pi)\). The distribution for \(M(h_b(1P)\pi)\) from data exhibits a clear two-peak structure without significant non-resonance component (Fig. 2 left). The distribution \(M(h_b(2P)\pi)\) behaves similarly with smaller statistics. These two structures are referred as \(Z_{b1}\) and \(Z_{b2}\) and parameterized as two P-wave Breit-Wigner amplitudes. The fit function with \(\sqrt{s} = M(h_b\pi)\) is:

\[
|BW(s, M_1, \Gamma_1) + ae^{i\phi}BW(s, M_2, \Gamma_2) + be^{i\psi}|^2 \frac{q_0}{\sqrt{s}}
\tag{1}
\]

Here the amplitude of two resonances and a non-resonant component are added coherently to form the rate, which is then multiplied with a phase-space factor \(\frac{q_0}{\sqrt{s}}\), where \(q\) or \(p\) is the momentum of the pion from \(\Upsilon(5S)\) or \(Z_b\) decay in the rest frame of their mother particles.

The \(Z_b\) particles can also be studied from the decay \(\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-\), with \(n = 1, 2, 3\). In this case, the final state particles can be fully reconstructed with \(\Upsilon(nS) \rightarrow \mu^+\mu^-\). Dalitz analysis is then performed to the three-body final states to extract maximal information. The amplitudes used in the parametrization includes two Breit-Wigners for \(Z_{b1}\) and \(Z_{b2}\), a coupled-channel Breit-Wigner for \(f_0(980)\) scalar, a Breit-Wigner for \(f_2(1270)\) tensor state, and a non-resonant amplitude. Results of \(Z_b\) parameters for all five channels are consistent, and the average masses and

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of three particles the transition from the first is close to 180° and the second is close to zero degree. From the distribution of $M(\Upsilon(2S)\pi)_{\text{max}}$, as shown in Fig. 2 (right), a large destructive interference dip near 10.6 GeV/$c^2$ suggests that this interference effect exists in the whole Dalitz plane, which is only possible if the $Z_b$ has a spin-parity $J^P = 1^+$. 

IV. $\eta_b$ PARTICLES

$h_b$ is expected to have large decay branching fractions to $\eta_b \gamma$ [11]. The $\eta_b$ particle previously has been studied [3, 4] at BaBar and CLEO in the channel $\Upsilon(3S) \rightarrow \eta_b \gamma$. Since large $h_b$ samples are available at Belle, it is natural to study the transition from $h_b$ to $\eta_b \gamma$.

The method to extract $\eta_b$ signals at Belle is similar to what is used in extracting $h_b$ signals. Here the missing mass of three particles $MM(\pi^+\pi^-\gamma)$ is calculated. To avoid the correlation between $MM(\pi^+\pi^-\gamma)$ and $MM(\pi^+\pi^-\mu)$, their difference is used, as $\Delta MM(\pi^+\pi^-\gamma) = MM(\pi^+\pi^-\gamma) - MM(\pi^+\pi^-\mu) + M(h_b)$, where $M(h_b)$ is fixed at the nominal value. The $MM(\pi^+\pi^-)$ spectra are then fitted in different $\Delta MM(\pi^+\pi^-\gamma)$ bins, to obtain the $h_b(1P, 2P)$ yields as a function of $\Delta MM(\pi^+\pi^-\gamma)$, as shown in Fig. 3 (a,b,c). The fact that $h_b$ is produced from the $Z_b$ resonances is used to suppress the background by the requirement $10.59\text{GeV}/c^2 < MM(\pi) < 10.67\text{GeV}/c^2$.

The $h_b(1P, 2P)$ yields as a function of $\Delta MM(\pi^+\pi^-\gamma)$ in $\eta_b(1S)$ and $\eta_b(2S)$ mass regions are fitted to a sum of the $\eta_b$ signal component and a smooth background component, for the transitions $h_b(1P) \rightarrow \eta_b(1S)\gamma$, $h_b(2P) \rightarrow \eta_b(1S)\gamma$, and $h_b(2P) \rightarrow \eta_b(2S)\gamma$. The signal is described by the convolution of a non-relativistic Breit-Wigner function with the resolution. At the time of this report, the fitted masses and widths are $m_{\eta_b(1S)} = 9402.4 \pm 1.5 \pm 1.8 \text{MeV}/c^2$, $\Gamma_{\eta_b(1S)} = 10.8^{+4.0+4.5}_{-3.7-2.0} \text{MeV}$, and $m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-2.9} \text{MeV}/c^2$ [12]. The hyperfine splittings $m_{\Upsilon(nS)} - m_{\eta_b(nS)}$ are determined as $\Delta M_{HF}(1S) = 57.9 \pm 2.3 \text{MeV}/c^2$, $\Delta M_{HF}(2S) = 24.3^{+4.0}_{-4.5} \text{MeV}/c^2$. This agrees with the theoretical calculations [13]. S.Dobbs et al. studied the $\eta_b(2S)$ in the process $\Upsilon(2S) \rightarrow \gamma\eta_b(2S)$ in CLEO data, by reconstructing 26 exclusive modes together for the $\eta_b(2S)$ candidate. The hyperfine splitting is reported as $\Delta M_{HF}(2S) = 48.7 \pm 2.7 \text{MeV}/c^2$ [14]. Fig. 3 (d) shows the fit. This is of about 5 sigma discrepancy compared to the Belle result and is in strong disagreement with theory. So further experimental clarification is needed.
FIG. 3: For Belle data [12], the $h_b(1P)$, $h_b(2P)$ yields in the $\eta_b(1S)$ region are shown in (a), (b) and the $h_b(2P)$ yield in the $\eta_b(2S)$ region is shown in (c). Clear $\eta_b(1S)$ and $\eta_b(2S)$ signals are all seen in (a,b,c). The mass difference between $\Upsilon(2S)$ and $\eta_b(2S)$ candidates in CLEO data [14] is shown in (d), where the unidentified small peak around 50 MeV is interpreted as the $\eta_b(2S)$ signal.

V. $\eta$ TRANSITIONS OF $\Upsilon(nS)$ AND OTHER $\Upsilon(5S)$ DECAYS

The transition $\Upsilon(nS) \rightarrow \eta\Upsilon(mS)$ is a spin-flip E1M2 transition. From the QCD multipole formalism [15], this spin-slip amplitude scales as $1/m_b$, and this $\eta$ transition is suppressed compared to the $\pi\pi$ transition. However, the experimental values do not support those predictions. Scaling from the known branching fraction $\psi' \rightarrow \eta J/\psi$, the branching fraction of $\Upsilon(2S) \rightarrow \Upsilon(1S)\eta$ should be around $8 \times 10^{-4}$, but the experimental value is around $2 \times 10^{-4}$ [16]. In addition, from Ref. [17], the relation $B(\Upsilon(4S) \rightarrow \Upsilon(1S)\eta) \approx 2.5 \times B(\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-)$ contradicts with the expected suppression in $\eta$ transition. So it is important to study more in these channels.

Belle performed a study of $\Upsilon(2S) \rightarrow (\eta, \pi^0)\Upsilon(1S)$ using Belle’s 24.7 fb$^{-1}$ $\Upsilon(2S)$ data. The reconstruction of $\Upsilon(1S) \rightarrow e^+e^-, \mu^+\mu^-$ and a small total reconstructed momentum in the $\Upsilon(5S)$ center-of-mass frame are required. By fitting the $\eta$ candidate and $\gamma\gamma$ masses, as shown in Fig. [18] we obtain $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\eta) = (3.41 \pm 0.30 \pm 0.35) \times 10^{-4}$ and $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0) < 4.3 \times 10^{-5}$ (90% CL).

The $\Upsilon(5S)$ data was also analyzed similarly to search for transitions to $\Upsilon(1,2S)\pi^+\pi^-\gamma\gamma$ states, with $\Upsilon(1,2S)$ reconstructed in the $\mu^+\mu^-$ channel. If we require the $\eta \rightarrow \pi^+\pi^-\pi^0$ selection criterion for the pions and photons, $\eta$ transition of $\Upsilon(5S)$ can be studied. At the same time, if we require the $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ selection, $\Upsilon(5S) \rightarrow \Upsilon(2S)\eta$ can also be studied, since the remaining two $\gamma$s can make an $\eta$. This time we simply fit the difference of the $\Upsilon(5S)$ candidate’s energy and beam energy in the center-of-mass system to extract the signal. This method gave the same result as fitting the missing mass of $\eta$. We found $B(\Upsilon(5S) \rightarrow \Upsilon(1S)\eta) = (7.3 \pm 1.6 \pm 0.8) \times 10^{-4}$, $B(\Upsilon(5S) \rightarrow \Upsilon(2S)\eta) = (38 \pm 4 \pm 5) \times 10^{-4}$, and $B(\Upsilon(5S) \rightarrow \Upsilon(1S)\eta') < 1.2 \times 10^{-4}$ (90% CL). Fig. [19] (a,b) shows...
FIG. 1: From top to bottom: mass distribution of the \( \eta \) candidates from \( \gamma \gamma \) and \( \pi^+ \pi^- \pi^0 \) channels are combined.

FIG. 4: \( \eta \) (left) and \( \gamma \gamma \) (right) mass distributions in the \( \Upsilon(2S) \rightarrow \eta \Upsilon(1S) \) and \( \Upsilon(2S) \rightarrow \pi^0 \Upsilon(1S) \) search at Belle. \( \eta \) candidates are combined from \( \gamma \gamma \) and \( \pi^+ \pi^- \pi^0 \) channels.

FIG. 5: Plots of \( \Upsilon(5S) \rightarrow \Upsilon(1,2S)\pi^+\pi^-\gamma \gamma \) study at Belle. Look-back plots for the missing mass of \( \eta \) in the \( \Upsilon(5S) \rightarrow \Upsilon(1,2S)\eta(\pi^+\pi^-\pi^0) \) study (a) and the \( \gamma \gamma \) mass in the \( \Upsilon(5S) \rightarrow \Upsilon(2S)(\Upsilon(1S)\pi^+\pi^-)\eta \) study (b) are shown. Missing mass of \( \pi^+\pi^- \) after the \( \chi_{b1,2} \rightarrow \Upsilon(1S)\gamma \) selection is shown in (c), where the left, middle, right peaks are due to \( \Upsilon(2S)\pi^+\pi^- \), the signal \( \Upsilon(1D)\pi^+\pi^- \), and the \( \Upsilon(2S)(\Upsilon(1S)\pi^+\pi^-)\eta(\gamma \gamma) \) reflection.

the look-back plots of the first two modes.

A peak of \( \Upsilon(1D) \) was seen in the inclusive distribution of missing mass of \( \pi^+\pi^- \) where the \( h_b \) states was observed (Fig. 1). A more complete study of the decay \( \Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^- \) is now possible when the exclusive mode \( \Upsilon(1,2S)\pi^+\pi^-\gamma \gamma \) is being analyzed, since we can aim for the sequential decay of \( \Upsilon(1D) \rightarrow \chi_{b}\gamma \rightarrow \Upsilon(1S)\gamma \gamma \). The peak of \( \Upsilon(1D) \) became clearer after this exclusive reconstruction, and turned out to be even sharper after the \( \chi_{b1,2} \rightarrow \Upsilon(1S)\gamma \) selection. From the fit shown in Fig. 5(c), we obtain the observation of this channel with \( B(\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-) \times B(\Upsilon(1D) \rightarrow \chi_{b1,2}(1P)\gamma) \times B(\chi_{b1,2}(1P) \rightarrow \Upsilon(1S)\gamma) = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4} \).

VI. SUMMARY

Belle’s large \( \Upsilon(5S) \) data provided many new results of bottomonium states. The inclusive spectra of \( \gamma, \pi^0, \pi^+\pi^- \), etc. provide the main method used in the discovery of new states from 27 years ago till now. Four new bottomonium states \( h_b(1P), h_b(2P), Z^+_b, Z^+_b \) were observed at Belle, where the \( \Upsilon(5S) \) behaves like the particle \( Y(4260) \) in the charm sector. Observations of the \( h_b(1,2P) \rightarrow \eta_b(1S)\gamma \) and \( h_b(2P) \rightarrow \eta_b(2S)\gamma \) were made. The particle \( \eta_b(2S) \) was observed for the first time and the hyperfine splitting \( \Delta M_{HF}(2S) \) at Belle agrees with theory. S.Dobbs et al. obtained a higher value \( \Delta M_{HF}(2S) \) from CLEO data and two results are in clear disagreement. For the other transitions of the \( \Upsilon(5S) \), observations of \( \Upsilon(5S) \rightarrow \Upsilon(1,2S)\eta \) and \( \Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^- \) channels were made. For the \( \eta \) transition of other \( \Upsilon \) particles, The new measurement of \( \Upsilon(2S) \rightarrow \Upsilon(1S)\eta \) branching fraction is still smaller

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than theory prediction. Finally, In the talk covered by Andre Chisholm, ATLAS and D0 has observed the $\chi_b(3P)$ state from the transition $\chi_b(3P) \rightarrow \Upsilon(1S,2S)\gamma$. In future, we expect more Belle results, and new results from the Hadron colliders.

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