Results on Charmonium(-like) and Bottomonium(-like) States from Belle and BaBar

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Abstract. Spectroscopy results for Belle and BaBar are reported. A particular focus is put on new results of the X(3872) state with its radiative decays to $J/\psi\gamma$ and $\psi'\gamma$, its decay into $J/\psi 3\pi$ and the search for production in radiative Upsilon decays. Another focus is L=2 mesons, in particlar a possible D-wave assignment to the X(3872) and the confirmation of an Upsilon D-wave state.

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INTRODUCTION

In this paper, spectroscopy results from the two B factories BaBar [1] at PEP-II and from Belle [2] at KEKB are reported. The data samples of the two experiments are summarized in Tab. 1.
There is quite a number of unresolved interesting questions in charmonium spectroscopy, such as:

- The charmonium potential is usually regarded as a static quark-antiquark potential (Cornell ansatz) [3]

$$V(r) = -\frac{4}{3}\frac{\alpha_S}{r} + k \cdot r \tag{1}$$

  with a Coulomb-like term and a confinement term. As can be seen, α_S is assumed fixed over the total range $0<r<\simeq 1$ fm, which is an approximation. Also, as the mechanism of confinement is still one of the unanswered questions in QCD, it is still unproven if the linear approximation (corresponding to a constant string force) in the confinement term is *(a)* valid to all orders of α_S and *(b)* valid even in the far long range $r>\simeq 1.3$ fm (i.e. in the string breaking regime). In fact, studies of potential constructed with two-gluon exchanges [4] [5] lead to a number of additional terms with different r dependances. In addition, the high lying states (e.g. $L\leq 2$, $n\geq 3$) are sensitive to the string constant $k\simeq 1$ GeV/fm, which is the slope of the confinement term, and mass measurements can provide a precise measurement of k.
- The strong coupling constant in the charmonium system has a quite high value α_S=0.54 [6], so there might be non-perturbative effects becoming visible e.g. in the hyperfine splittings.
- What is the nature of the newly observed narrow states near thresholds, which do not fit into potential model calculations? Are they molecular states? Or tetraquarks? Or threshold effects? As an example, molecular potentails might contain r^{-2} and r^{-3} [7] terms, not present in the Cornell potential, and leading to eigenstates with masses different from the quark-antiquark potential.
- There are yet unobserved states, some of them expected narrow, e.g. the $^3D_2$(J^{PC}=2^{--}) state.

Similar questions apply to the bottomonium system. At B factories, studies of bottomonium require the change of the beam energies. A few results are reported down below.

TABLE 1. Integrated luminosities for data sets at different beam energies for BaBar and Belle.

	Belle	**BaBar**
On-resonance		
Υ(4S)	711 fb^{-1}	433 fb^{-1}
Υ(5S)	121 fb^{-1}	– fb^{-1}
Υ(3S)	3.0 fb^{-1}	30 fb^{-1}
Υ(2S)	24 fb^{-1}	14 fb^{-1}
Υ(1S)	5.7 fb^{-1}	– fb^{-1}
Off-resonance		
	87 fb^{-1}	54 fb^{-1}
Total	952 fb^{-1}	553 fb^{-1}

WIDTH OF η_c

Although the η_c is the ground state of the charmonium system (J^{PC}=0^{-+}, $^1S_0$) and already discovered in 1980 [11] [12], its width has been of particular interest recently. Previous width measurements [17] showed values around $\Gamma\simeq$15 MeV from radiative J/ψ and ψ' decays, and values around $\Gamma\simeq$30 MeV from B meson decays. However, this is probably not surprising, as in the radiative decays the cross section varies according to E_γ^a with an exponent a=3−7. This energy dependance modifies the lineshape and the width determination becomes non-trivial. On the other hand, in the reaction $\gamma\gamma\to\eta_c$ the Breit-Wigner line shape is an appropriate approximation. In a new high statistics measurement by BaBar with a data set of 469 fb^{-1} and 14090 η_c signal events, a high precision measurement of the mass m=2982.2±0.4±1.6 MeV and the width Γ=31.7±1.2±0.8 MeV of the η_c could be obtained. This measurement represents a factor $\simeq$3 improvement in both statistical and systematic errors compared to the BaBar measurement in 2008 in B meson decays [9] and the Belle measurement in 2008 in $\gamma\gamma$ collisions [10].

Decays of X(3872) to $D\overline{D}^*$

The X(3872) state has been discovered in B meson decays in the decay X(3872)$\to J/\psi\pi^+\pi^-$ by Belle [13]. It was confirmed in the same process by BaBar [14] and confirmed in inclusive production in $p\overline{p}$ production at $\sqrt{s}$=1.8 TeV at CDF-II [15] and D0 [16]. Among the newly observed charmonium-like states (sometimes referred to as XYZ states) the X(3872) is the only one with several decay channels having been observed. It has a surprisingly very narrow width Γ<2.3 MeV [13], although its mass is above the open charm threshold. As its mass with 3871.56±0.22 MeV [17] is very close (within 1 MeV) to the D^0D^{0*} threshold, it was discussed as a possible S-wave $[D^0D^{0*}]$ molecule [18] [19]. The decay into $D^\pm D^{\mp*}$ is kinematically forbidden, but the decay into D^0D^{0*} is a strong decay and among the so far observed decays it represents the dominant one, i.e. the branching fraction is a factor $\simeq$9 higher than for the decay into $J/\psi\pi^+\pi^-$. In this decay channel, BaBar measured surprisingly a high mass of the X(3872) as m=3875.1$^{+0.7}_{-0.5}$(stat.)±0.5(syst.) MeV [20]. This high value initiated discussion, that there might be two different X states, namely X(3872) and X(3875), which would fit to a tetraquark hypothesis [21] and the two different states $[c\bar{c}u\bar{u}]$ and $[c\bar{c}d\bar{d}]$. On the other hand Belle measured in the same decay channel the mass as m=3872.9$^{+0.6}_{-0.4}$(stat.)$^{+0.4}_{-0.5}$(syst.) MeV [22] and thus consistent with the world average [17]. A possible explanation of the discrepancy is the difficulty of performing fits to signals close to threshold. In fact, the two fits used two very different approaches:

- Babar used a 1-dimensional binned maximum likelihood fit [20] with the D^*D invariant mass as the only variable, where the signal probability density function was extracted from MC simulations and an exponential function was used for the background parametrization.
- Belle used an 2-dimensional unbinned maximum likelihood fit [22], i.e. on the one hand the beam constraint mass with a Gaussian signal and an Argus function for the background, and on the other hand a Breit-Wigner signal for the D^*D invariant mass with a square root function for the background.

Radiative Decays of X(3872)

The branching fraction of the rare decay X(3872)$\rightarrow J/\psi\gamma$ is a factor $\simeq$6 smaller than the one for X(3872)$\rightarrow J/\psi\pi^+\pi^-$. The first evidence by Belle [23] was based upon a data set of 256 fb^{-1} with 13.6$\pm$4.4 signal events. The signal was confirmed by BaBar [24] with a data set of 424 fb^{-1} and 23.0$\pm$6.4 signal events. Although rare, this decay channel is very important, as their observation clearly establishes a C=+1 charge parity assignment to the X(3872).
Recently BaBar found evidence for the decay X(3872)$\rightarrow\psi'\gamma$ [25] with 424 fb^{-1} and 25.4$\pm$7.4 signal events. The signal yield of this observation was surprising, as it implied a large ratio BR(X(3872)$\rightarrow\psi'\gamma$)/ BR(X(3872)$\rightarrow J/\psi\gamma$)=3.4$\pm$1.4. There was a priori no understanding of the fact, why the transition of the X(3872) to a n=2 charmonium state should be stronger than to n=1. In fact, quite the opposite behaviour was expected.
In case of X(3872)$\rightarrow J/\psi\gamma$ the photon energy is E_γ=775 MeV, and thus due to vector meson dominance ρ and ω can contribute to the amplitudes. However, in case of X(3872)$\rightarrow\psi'\gamma$ with the smaller E_γ=186 MeV the transition can only proceed through light quark annihilation with an expected small amplitude. A new measurement by Belle of both radiative channels was based upon a data set of 711 fb^{-1} [26]. The background was studied in MC simulations and revealed peaking behaviour in some background components close to the signal region. The signal X(3872)$\rightarrow J/\psi\gamma$ was clearly reestablished with $30.0^{+8.2}_{-7.4}$ signal events (4.9σ significance) for $B^+\rightarrow K^+$X(3872) and $5.7^{+3.5}_{-2.8}$ signal events (2.4σ significance) for $B^0\rightarrow K^0$X(3872).

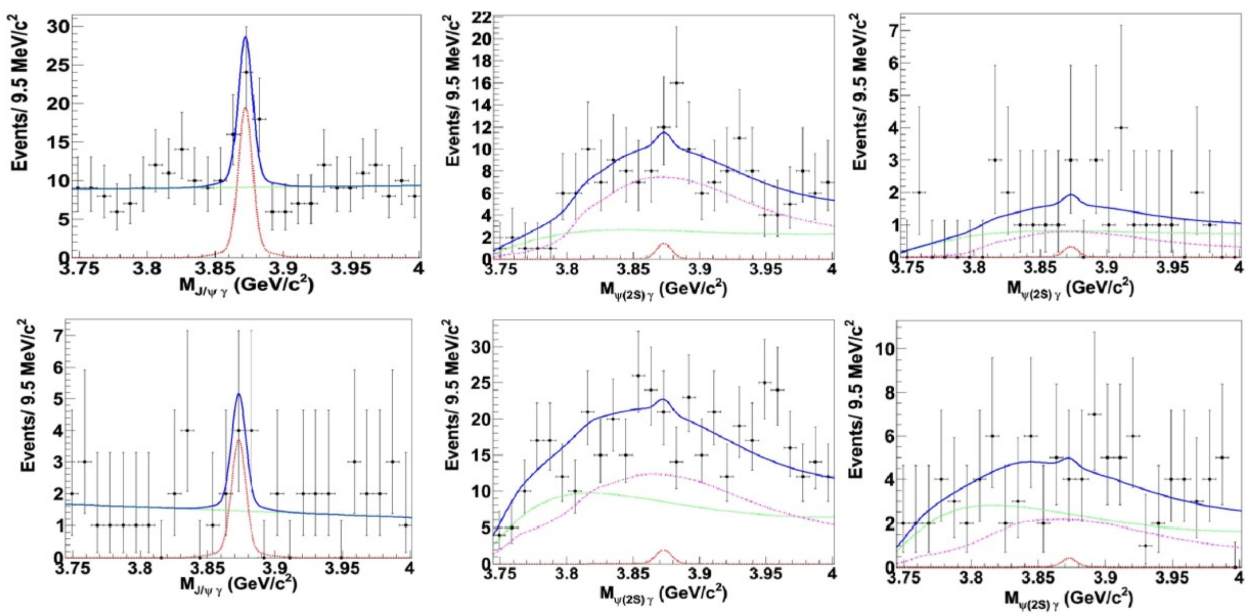

FIGURE 1. Preliminary Belle results on radiative decays of the X(3872). $J/\psi\gamma$ invariant mass in the X(3872) mass region for $B^+\rightarrow K^+$X(3872)($\rightarrow J/\psi\gamma$) (top left) and $B^0\rightarrow K^0_s$X(3872)($\rightarrow J/\psi\gamma$) (bottom left), and $\psi'\gamma$ invariant mass in the X(3872) mass region for $B^+\rightarrow K^+$X(3872)($\rightarrow\psi'\gamma$) (top center) $B^0\rightarrow K^0_s$X(3872)($\rightarrow\psi'\gamma$) (bottom center) with $\psi'\rightarrow e^+e^-,\mu^+\mu^-$ and $B^+\rightarrow K^+$X(3872)($\rightarrow\psi'\gamma$) (top right) $B^0\rightarrow K^0_s$X(3872)($\rightarrow\psi'\gamma$) (bottom right) with $\psi'\rightarrow J/\psi\pi^+\pi^-$. The solid, dotted and dot-dashed curves are the total, combinatorial background and combined $\psi'K^*$ and $\psi'K$ background, respectively. The background subtracted signal is also shown.

For X(3872)$\rightarrow\psi'\gamma$, the four decay channels $B^+\rightarrow K^+$X(3872) and $B^0\rightarrow K^0$X(3872) with $X(3872)\rightarrow\psi'\gamma$ with $\psi'\rightarrow l^+l^-$ and $\psi'\rightarrow J/\psi\pi^+\pi^-$. Charged and neutral B modes were treated separately, but the two ψ' subdecay modes were fitted simultaneously because of their different background shapes. The signal was treated as a double Gaussian, the combinatorial background was parameterized as a threshold function. The shape of the $\psi'K^*$ and $\psi'K$ background, and in particular the peaking structures, was modeled as a sum of bifurcated gaussians using a large MC sample. The signal yields were determined as $5.0^{+11.9}_{-11.0}$ signal events (0.4σ significance) for $B^+\rightarrow K^+$X(3872) and $1.5^{+4.8}_{-3.9}$ signal events (0.2σ significance) for $B^0\rightarrow K^0$X(3872). Thus, contrary to BaBar, Belle observed no signal, which would imply that there is no indication that the radiative transition from X(3872) to n=2 charmonium is stronger than to n=1

charmonium.
In the same analysis, the decay $\chi_{c1,2}{\to}J/\psi\gamma$ was used as a reference channel with signal yields of $32.8^{+10.9}_{-10.2}$ (3.6σ significance) for $B^+{\to}K^+\chi_{c2}$ and $2.8^{+4.7}_{-3.9}$ (0.7σ significance) for $B^0{\to}K^0\chi_{c2}$. In the charged mode, this represents the first observation of a J^P=2^+ state in a rare exclusive final state in a B meson decay, and thus a transition $0^-{\to}0^-2^+$.

Decays of X(3872) and Y(3940) into $J/\psi 3\pi$

As the ρ meson carries isospin I=1, the X(3872) seems to violate isospin conservation in the decay X(3872)$\to J/\psi\rho(\to\pi^+\pi^-)$. One of the proposed explanations [27] is ρ/ω mixing, and therefore the investigation of the decay X(3872)$\to J/\psi\omega(\to\pi^+\pi^-\pi^0)$ is of importance. The difficulty hereby is the nearby Y(3940) state, which is also known to decay into the same final state. The latter decay was investigated be Belle with a data set of 275×10^6 B meson pairs. The mass of the Y(3940) was determined as 3943 ± 11(stat.)±13(syst.) MeV with a width of 87 ± 22(stat.)±26(syst.) MeV. Belle also observed a signal for X(3872)$\to J/\psi\omega(\to\pi^+\pi^-\pi^0)$, based upon a data set of 256 fb^{-1} [29]. The measured efficiency corrected ratio of X(3872)$\to J/\psi\pi^+\pi^-\pi^0$/ X(3872)$\to J/\psi\pi^+\pi^-$= 1.0 ± 0.4(stat.)±0.3(syst.) indicated another case of isospin violation due to the additional π^0. BaBar published slightly different values for the Y(3940) with a data set of 383×10^6 B meson pairs mass [30], namely a mass of $3914.6^{+3.8}_{-3.4}$(stat.)±2.0(syst.) MeV and a width of 34^{+12}_{-8}(stat.)±5(syst.) MeV. However, a signal for X(3872)$\to J/\psi\omega(\to\pi^+\pi^-\pi^0)$ was not observed. In a recent re-analysis with 433 fb^{-1} by BaBar, a requirement on the 3-pion mass was adjusted, i.e. the lower offset was extended from 0.7695 GeV to 0.7400 GeV. With this change in the analysis technique BaBar was able to confirm the Belle signal for X(3872)$\to J/\psi\omega(\to\pi^+\pi^-\pi^0)$ and confirm the large isospin violation for the ratio X(3872)$\to J/\psi\pi^+\pi^-\pi^0$/ X(3872)$\to J/\psi\pi^+\pi^-$ measured as 0.7 ± 0.3(stat.) and 1.7 ± 1.3(stat.) for B^+ and B^0 decays, respectively.
In the re-analysis, BaBar also investigated the shape of the 3π mass distribution in order to determine the quantum number of the X(3872). A similar analysis for the 2π mass distribution in case of X(3872)$\to J/\psi\pi^+\pi^-$ was performed before by Belle [32] and CDF-II [33]. The result in both cases was that S-wave is preferred. However, in the new BaBar analysis the shape of the 3π mass distribution seems to indicate that P-wave is preferred. For the 2π case and S-wave, a parity of $+1$ for the X(3872) is preferred, leading to a tentative assignment of J^{PC}=1^{++}. This quantum number assignment is also supported by angular analyses [29] [34] and leads to a possible charmonium state assignment of χ'_{c1} ($^3P_1$), which is an n=2 state with a mass of 3953 MeV as predicted by potential models [6] and thus $\simeq$70 MeV too high compared to the observation. For the 3π case and P-wave, a parity of -1 for the X(3872) is preferred, leading to a possible assignment of J^{PC}=2^{-+}. Then a possible charmonium assignment is η_{c2} ($^1D_2$), which is an n=1 state. The predicted mass is $\simeq$100 MeV lower than for the χ'_{c1}. This state would be an L=2 meson.
In a different analysis, Belle investigated the $J/\psi\omega$ final state in $\gamma\gamma$ collisions based upon 694 fb^{-1} [35]. This analysis not only uses Υ(4S), but also Υ(3S) and Υ(5S) data (see Tab. 1). The event selection uses a p_T<0.1 GeV/c balance requirement. The final state in $\gamma\gamma$ collisions is required to have isospin I=0. Fig. 2 shows the W distribution of the final candidate events, where W is defined as W=m_5-$m(l^+l^-)$+$m_{J/\psi}$. m_5 is the invariant mass of the system constructed from four charged tracks and a neutral pion candidate. A clear enhancement seen just above $J/\psi\omega$ threshold with 49 ± 14(stat.)±4(syst.) events (7.7σ stat. significance). The fitted mass is 3915 ± 3(stat.)±2(syst.) MeV, thus it might be the observation the Y(3940) state in a second production mode. However, the fitted width is Γ=17 ± 10(stat.)±3(syst.) MeV, which is narrower than the width of the Y(3940) as measured in B decays. The production mode allows to establish the charge parity C=$+1$ for this state, same as the X(3872), but the determination of the other quantum numbers would require more statistics.

Υ(1S) Radiative Decays to X(3872)

As shown in Tab. 1, Belle recorded an extensive data set with the beam energies adjusted to the Υ(1S) resonance, the n=1 $^3S_1$ $b\bar{b}$ state with J^P=1^- and a mass of 9.46 GeV. With this data set, radiative transistions $b\bar{b}{\to}c\bar{c}\gamma$ can be investigated. These rare events with an expected branching fraction of $\leq10^{-5}$ [36] with interfering QED and QCD amplitudes. The transition may be from a 1^{--} state, such as the Υ(1S), to a 1^{++} state, which is one of the most probably quantum number assignments for the X(3872).
Belle searched for the process Υ(1S)$\to\gamma$X(3872)$(\to J/\psi\pi^+\pi^-)$ with a data set of 5.712 fb^{-1} [37], corresponding to 88×10^6 Υ(1S) decays The photon detection required E_γ^{lab}>3.5 GeV and the recoil mass on four charged

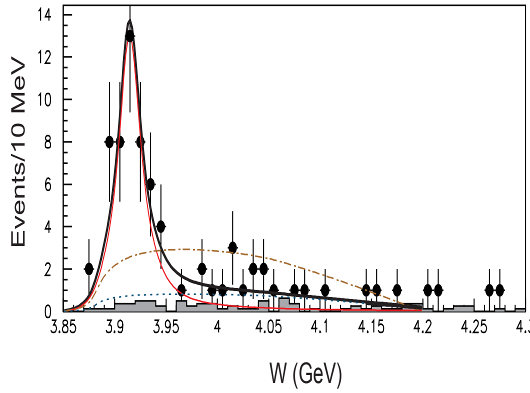

FIGURE 2. The W distribution of the final candidate events (dots with error bars) for $\gamma\gamma \to J/\psi\omega$ at Belle [35]. The shaded histogram is the distribution of non-J/ψ background estimated from the sideband distribution. The bold solid, thinner solid and dashed curves are the total, resonance and background contributions, respectively. The dot-dashed curve is the fit without a resonance.

tracks being consistent with zero, i.e. $-2 < m_{recoil} < 2$ GeV^2. Initial state radiation (ISR) was treated in two different ways. On the one hand, ISR events were rejected by a criterium on the cms polar angle of the photon, i.e. $|\cos\vartheta^*_\gamma| < 0.9$ On the other end, ISR events for ψ' production, with the same $J/\psi\pi^+\pi^-$ final state as the X(3872), were used as a crosscheck, and the cross section for this ISR process was determined as 20.2±1.1(stat.) pb. For the X(3872) one event in the signal region was observed, resulting in an upper limit for the product branching fraction BR(Y(1S)$\to\gamma$X(3872)$\times$BR(X(3872)$\to J/\psi\pi^+\pi^-$)$<2.2\times10^{-6}$ at 90% CL.

THE Υ(1D) STATE

D-wave mesons with orbital angular momentum L=2 are quite different, if we compare the charmonium and the bottonium system. For the charmonium system, there are two observed D-wave states *above* the $D\overline{D}$ threshold, namely the ψ(3770) (n=1) and the ψ(4153) (n=2). Both are $J^{PC}=1^{--}$ and broad, i.e. their experimentally measured width is >20 MeV. For the bottomonium system, there are two D-wave states predicted *below* threshold and thus narrow, i.e. their hadronic width $\leq$30 keV [38]. Consequently, in case of an observation it might even be possible to resolve the triplet of $J^{PC}=0^{--}$, 1^{--} and 2^{--}. An $\Upsilon(1^3D_2)$ candidate was observed by CLEO [39] based upon 5.8×10^6 Υ(3S) decays with a mass of 10161.1±0.6±1.6 MeV, consistent with a potential model prediction of 10158 MeV [40].
BaBar searched for the $\Upsilon(1^3D_2)$ in a data set of 122×10^6 Υ(3S) decays [41]. The signal path has two radiative transitions $\Upsilon(3S)\to\Upsilon(2P)\gamma$ and $\Upsilon(2P)\to\Upsilon(1D)\gamma$, used for tagging, with subsequent decay by emission of a $\pi^+\pi^-$ pair to Υ(1S), which finally decays to e^+e^- or $\mu^+\mu^-$. The complete signal path was required for the identification. BaBar was able to clearly confirm the $J^{PC}=1^{--}$ state with $33.9^{+8.2}_{-7.5}$ signal events (5.8σ stat. significance). The fitted mass is m=10164.5±0.8±0.5 MeV, consistent with the CLEO measurement.

SUMMARY

The B factories continue to provide exciting results. Charmonium spectroscopy is studied in B meson decays, $\gamma\gamma$ collisions and $\Upsilon(n\mathrm{S})$ decays. Bottomonium spectroscopy is studied in $\Upsilon(n\mathrm{S})$ decays. Highly excited states such as L=2 states are clearly identified and provide accurate tests for potential models. States which are not consistent with any potential model, such as the X(3872), are studied in new ways, such as radiative decays or production in radiative decays. Surprising properties such as large isospin violation are confirmed.

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REFERENCES

1. BaBar Collaboration, NIM A479(2002)1
2. Belle Collaboration, NIM A479(2002)117
3. E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, T.-M. Yan, Phys. Rev. D17(1978)3090
4. S. N. Gupta, S. F. Radford, W. W. Repko, Phys. Rev. D26(1982)3305
5. S. Titard, F. J. Yndurain, Phys. Rev. D49(1994)6007
6. Barnes, Godfrey, Swanson, Phys. Rev. D72(2005)054026
7. C. Amsler, N. A. Törnqvist, Phys. Rep. 389(2004)61
8. BaBar Collaboration, Phys. Rev. D81(2010)052010
9. BaBar Collaboration, Phys. Rev. D78(2008)012006
10. Belle Collaboration, EPJ C53(2008)1
11. Mark-II Collaboration, Phys. Rev. Lett. 45(1980)1146
12. Crystal Ball Collaboration, Phys. Rev. Lett. 45(1980)1150
13. Belle Collaboration, Phys. Rev. Lett. 91(2003)262001
14. BaBar Collaboration, Phys. Rev. D71(2005)071103
15. CDF-II Collaboration, Phys. Rev. Lett. 93(2004)072001
16. D0 Collaboration, Phys. Rev. Lett. 93(2004)162002
17. K. Nakamura et al. (Particle Data Group), J. Phys. G37(2010)075021
18. N. A. Tornqvist, Phys. Lett. B590(2004)209
19. N. A. Tornqvist, Phys. Rev. Lett. 67(1991)556
20. BaBar Collaboration, Phys. Rev. D77(2008)011102
21. L. Maiani, A. D. Polosa, V. Riquer, Phys. Rev. Lett. 99(2007)182003
22. Belle Collaboration, Phys. Rev. D81(2010)031103
23. Belle Collaboration, arXiv:hep-ex/0505037
24. BaBar Collaboration, Phys. Rev. D74(2006)071101
25. BaBar Collaboration, Phys. Rev. Lett. 102(2009)132001
26. V. Bhardwaj, for the Belle Collaboration, QWG10, International Workshop on Heavy Quarkonium 2010, Fermilab, Batavia, May 18-21, 2010
27. K. Terasaki, Prog. Theor. Phys. 122(2010)1285
28. Belle Collaboration, Phys. Rev. Lett. 94(2005)182002
29. Belle Collaboration, hep-ex/0505037
30. BaBar Collaboration, Phys. Rev. Lett. 101(2008)082001
31. BaBar Collaboration, arXiv:1005.5190
32. Belle Collaboration, arXiv:hep-ex/0505038
33. CDF-II Collaboration, PRL 96(2006)102002
34. CDF-II Collaboration, PRL98(2007)132002
35. Belle Collaboration, Phys. Rev. Lett. 104(2010)092001
36. Y.-J. Gao, Y.-J. Zhang, K.-T. Chao, hep-ph/0701009
37. Belle Collaboration, Phys. Rev. D82(2010)051504
38. W. Kwong, Phys. Rev. D38(1988)279
39. CLEO Collaboration, Phys. Rev. D70(2004)032001
40. D. Ebert, R. N. Faustov, V. O. Galkin, Phys. Rev. D67(2003)014027
41. BaBar Collaboration, arXiv:1004.0175 [hep-ex]