A Uniform Description of the States Recently Observed at B-factories

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Abstract

The newly found states Y(4260), Y(4361), Y(4664) and Z\(^\pm\)(4430) stir broad interest in the study of spectroscopy in a typical charmonium scale. The Y(4260) which was observed earlier has been interpreted as hybrid, molecular state, and baryonium, etc. In this note we show for the first time that these new structures, which are hard to be interpreted as charmonium states, can be systematically embedded into an extended baryonium picture. According to this assignment, the so far known characters of these states are understandable. And, in the same framework, we make some predictions for experimenters to measure in the future.

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Recently, a series of new resonances in the range of 3.8 ∼ 5.5 GeV were observed in experiment. Among them, the Y(4260), Y(4361), Y(4664) and Z±(4430) have distinct characters from others. They are hard to be embedded into the regular charmonium spectroscopy, which means that they may have exotic natures. Of these four states, Y(4260) was first observed by the BaBar Collaboration in the initial-state radiation process \( e^+e^- \rightarrow \gamma_{\text{ISR}} \pi^+\pi^-J/\psi \) with a mass of 4259 ±8 ±4 MeV and total decay width of 88 ±23 ±5 MeV \(^4\). Obviously, this state possesses the same quantum numbers as photon, i.e. \( J^{PC} = 1^{--} \). Since the mass of Y(4260) lies in the range of regular charmonium states, a natural interpretation for it is that it contains charm-anticharm constituents. However, although the structure exhibits at about 4.26 GeV, much higher than the open-charm threshold, so far the exclusive \( D\bar{D} \) decay mode has not been reported. The Y(4260) was later confirmed by CLEO \(^2\) and Belle Collaborations \(^3\).

In theory, several models were proposed to explain it. Except for Ref.\(^4\) where the Y(4260) was still interpreted as a normal member in the charmonium spectra, a common belief is that it is rather an exotic (or cryptoexotic) state. The authors of Refs. \(^5\) \(^6\) \(^7\) proposed that the new state is a charmonium hybrid that is constructed by a pair of charm-anticharm quarks and a gluon. Ref. \(^8\) treats Y(4260) as the first orbital excitation of a diquark-antidiquark state \([cs][\bar{c}\bar{s}]\). In Ref. \(^9\), Liu et al. explained the resonance as a molecular state being composed of \( \rho \) and \( \chi_c \), while the authors of Ref. \(^10\) took it as a \( \omega \) and \( \chi_c \) molecular state. And, in Ref. \(^11\) the Y(4260) was interpreted as a baryonium state containing hidden charm and is made out of \( \Lambda_c^+\Lambda_c^- \), or triquark-antitriquark pair.

Of the existing models, the CLEO data are still consistent with the hybrid and baryonium models. And, it should be noticed that there exists a misunderstanding that the CLEO measurement of the ratio \(^2\)

\[
\Gamma[Y(4260) \rightarrow \pi^0\pi^0\psi] \approx \frac{1}{2}\Gamma[Y(4260) \rightarrow \pi^+\pi^-\psi]
\]  

(1)

disfavors the baryonium model. In fact, it is exactly the baryonium model prediction \(^11\), and in principle it should also comply with other models having the \( J/\psi\pi\pi \) decay mode.

The Y(4361) was first observed by Babar Collaboration in the subsequent search for Y(4260) in process of \( e^+e^- \rightarrow \gamma_{\text{ISR}} \pi^+\pi^-J/\psi(2S) \) \(^12\). They found no obvious signature of Y(4260), but rather a new structure at 4324 ± 24 MeV with a width of 172 ± 33 MeV. Recently, this observation is confirmed by Belle Collaboration, and they find that in fact the structure 4324 MeV is composed of two resonant structures \(^13\). One at \( M = 4361 \pm 9 \pm 9 \) MeV with a width of \( 74 \pm 15 \pm 10 \) MeV, another at \( M = 4664 \pm 11 \pm 5 \) MeV with a width of \( 48 \pm 15 \pm 3 \) MeV, which we will refer as Y(4361) and Y(4664) respectively in the following discussion.

Although it is a bid hard to imagine that there are many \( 1^{--} \) vector hybrids in-between the range of one GeV, to distinguish the quark-antiquark-gluon hybrid model from the multiquark models in a single neutral state measurement looks difficult, since the gluon
of the hybrid can always split into quark pairs. A characteristic that can distinguish multiquark states from hybrids or charmonia is of the non-zero charge of the states in the charmonium energy region. A new structure of $Z(4433)$ was reported found in the process of $B \rightarrow KZ(4433) \rightarrow K\pi\psi(2S)$ by Belle Collaboration, in the recent Lepton-Photon 2007 symposium [14]. It has a mass of $M = 4433 \pm 4({\text{stat}}) \pm 1({\text{syst}})$ MeV and width $\Gamma = 44^{+17}_{-13}({\text{stat}})^{+30}_{-11}({\text{syst}})$ MeV. One unique nature of this new state is that it possesses electric charge (the $Z^+$ and its charge conjugation $Z^-$ are both observed). Since the statistical significance of the observation is greater than $7\sigma$, it deserves to be treated seriously.

Soon after the announcement of the observation of this new structure, $Z(4433)$, there appear couple of theoretical speculations on its nature. Refs. [15] and [16] suggest that it might be a $D^*(2010) - \bar{D}(2420)$ rescattering resonance, because its mass is in proximity to the $D^*(2010)\bar{D}(2420)$ threshold, while Bugg [17] takes it as a $D^*(2010)\bar{D}(2420)$ threshold cusp. Maiani et al. [18] interpret it as a tetraquark bound state, etc.

Since there are increasingly numerous new structures observed recently in the charmonium sector, it is tempting to give a uniform description of them, or at least some of them. According to Ref.[11], the $Y(4260)$ can be interpreted as a baryonium state of $\Lambda_c - \bar{\Lambda}_c$. If we extend this baryonium picture to include $\Sigma_c^0$ as a basic ingredient, the $\Lambda_c$ and $\Sigma_c^0$ can be taken as basis vectors in two-dimensional space, which is similar to the proton and neutron in constructing the pion by Fermi and Yang more than fifty years ago [19]. Approximately, we assume that the transformation in this two-dimensional ”C-spin” space is invariant, i.e., there exists a SU(2) symmetry between $\Lambda_c$ and $\Sigma_c^0$. Then, from this doublet one can make up four baryon-antibaryon configurations, the ”C-spin” triplet and singlet(note that the charged $\Sigma_c^0$ and $\Lambda_c$ can give a similar mass degenerate structure).

That is:

$$B_1^+ \equiv |\Lambda_c^+ \Sigma_c^0 >$$

$$B_0^0 \equiv \frac{1}{\sqrt{2}}(|\Lambda_c^+ \bar{\Lambda}_c > - |\Sigma_c^0 \Sigma_c^0 >)$$

$$B_1^- \equiv |\Lambda_c^- \Sigma_c^0 >$$

and

$$B_0^0 \equiv \frac{1}{\sqrt{2}}(|\Lambda_c^+ \bar{\Lambda}_c > + |\Sigma_c^0 \Sigma_c^0 >)$$

This is just an imitation of isospin for proton and neutron system.

Although in the baryonium picture there surely exits large symmetry broken effects, it is still possible to make a qualitative description of the mass spectrum. For $Z^+ (4433)$ and $Z^- (4433)$, which have the quantum number $J^P = 1^+$ (however, the $0^-$ and $1^-$ are not excluded [14]) and isospin $I = 1$, we find their correspondences are $\Lambda_c^+ \Sigma_c^0$ and $\Lambda_c^- \Sigma_c^0$, respectively. Since the $Z^\pm (4433)$ are found in the $K\pi\psi(2S)$ channel and there is no
signature found at the same energy region in the $K\pi J/\psi$ mode \cite{20}, it is plausible to consider $Z^{\pm}(4433)$ to be the first radial excitation of $\Lambda_c^+ \Sigma_c^0$, that is $B_1^{\pm *}$. Otherwise, on the other hand, the mass difference between $Y(4260)$ and $Z(4433)$ is too big, provided they are in the same triplet in (2). Therefore, in this assignment there should exist the charged states at mass of 4330 MeV or so, which correspond to the ground states composed of $\Lambda_c^\pm \Sigma_c^0$, i.e. $B_1^{\pm}$. The magnitude of 4330 MeV is obtained from the following arguments.

We know that $Y(4361)$ and $Y(4664)$ were observed in the $e^+e^- \rightarrow \gamma_{ISR} \pi^+\pi^-\psi(2S)$ process \cite{13}, and Belle found no structures in the same mass region in process of $e^+e^- \rightarrow \gamma_{ISR} \pi^+\pi^-J/\psi$. One of the possibilities is that these states are the first radial excitations of the heavy hidden quark pair, which may easily decay to $\psi(2S)$ rather than to $J/\psi$, relatively. Explicitly, $Y(4361)$ might be the radial excited state of $Y(4260)$ and $Y(4664)$ the radial excited state of the C-spin singlet \cite{3}. Of course, the reason why the energy gap between ground state and the first radial excitation is so small needs further investigation. From the formerly defined C-spin symmetry, the ground state of $Z(4433)$ should be around 4330 MeV, and the ground state for $Y(4664)$ should be around 4560 MeV. In fact from Ref.\cite{13} one can read an unclear structure around the 4500 MeV, which is left for further confirmation.

Except for above arguments, the PDG data read \cite{21}

$$M(Y(4361)) - 2M(\Lambda_c) \approx M(Y(4664)) - 2M(\Sigma_c) \approx M(Z(4433)) - M(\Lambda_c) - M(\Sigma_c) \approx M(4330?) - M(4260) - M(4560?) \approx 4000\text{MeV}. \quad (4)$$

Due to the existing uncertainties in the experimental measurement, the above relations should only be treated as an order-of-magnitude estimation. Nevertheless, the equation (4) in some sense supports the baryonium picture.

Table 1: The experimental measurements and baryonium model predictions (speculations) for spin triplet states $B$ and their radial excitations $B^*$. The question mark means unobserved in experiment, and the pseudoscalar partners of the listed states are all missing. The numbers in the brackets are in the units of MeV.

|                | $B_1^+(4330?)$ | $B_0^+(4260)$ | $B_1^-(4330?)$ | $B_0^-(4560?)$ |
|----------------|----------------|---------------|----------------|----------------|
| $B_1^{+*}(4430)$ | $B_1^{+*}(4361)$ | $B_1^{-*}(4430)$ | $B_0^{+*}(4664)$ |

Different from the model in Ref.\cite{11}, where the $Y(4260)$ was treated as a $\Lambda_c \bar{\Lambda}_c$ bound state, in the extended picture, the physical states of $Y(4260)$ and $Y(4560)$ (suppose the latter exists) are the mass eigenstates of two orthogonal vectors of (2) and (3) as given in Table 1. From the experimental measurement, one can infer that the $Y(4260)$ has a large component in $\Lambda_c \bar{\Lambda}_c$ configuration and $Y(4560)$ is mainly in $\Sigma_c^0 \Sigma_c^0$ configuration. If necessary, the mixing angle can be straightforwardly calculated.
In summary, in this paper we try in the first time to give a systematic description (speculation) of the newly observed structures(states) in B-factories. We assume that these states can be embedded into the multiquark picture, i.e., \((c[n][n] + \bar{c}[ar{n}][ar{n}])\), where the \([n]\) denotes for the light quarks u and d; and the hexaquark states are configured by the triquark-antitriquark clusters, namely, the baryonia. In comparison with the Teraquark model, the hexaquark scheme predicts that more rich spectrum in the charmonium sector may exist.

In this extended baryonium picture, there is an approximate C-spin symmetry. Four classes of baryonium states are predicted, three in triplet and one in singlet. This model is partially supported by the experimental data. We predict two vector-like structures could exist around 4560 MeV and 4330 MeV. The former should be neutral and the latter is charged. In addition, since the concerned states, Y(4260), Y(4361), Y(4664) and \(Z^{\pm}(4430)\), are vector states(the last one is not fully confirmed), if the baryonium picture is correct, their pseudoscalar para-baryonium partners should also exist. All these wait for future experiment to examine.

Last, it should be noted that our interpretation for the newly observed states Y(4260), Y(4361), Y(4664) and \(Z^{\pm}(4430)\) as baryonia is merely based on the quark model. From the success of quark model in describing the normal meson and baryon, we expect that this picture may give a qualitative description of those newly observed states at relatively low energy. For fine structures and exquisite natures of them, the involvement of QCD dynamics is unavoidable, which, although is one of our aims for further investigation, is beyond the scope of this brief report.

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