PHYSICAL REVIEW D **77,** 054001 (2008)

Partners of $Z(4430)$ and productions in B decays

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(Received 8 November 2007; published 3 March 2008)

Recently, the Belle Collaboration has reported a resonant state produced in $B \to K\pi\psi'$, which is called $Z(4430)$. This state is charged, so it can not be interpreted as an ordinary charmonium state. In this paper, we analyze the octet to which this particle belongs and predict the masses of mesons in this octet. Utilizing flavor SU(3) symmetry, we study production rates in several kinds of B decays. The $\bar{B}^0 \to Z_s^- \pi^+ \to K^- \psi' \pi^+$ and $B^- \to \bar{Z}_s^0 \pi^- \to K_S \psi' \pi^-$ decay channels, favored by Cabibbo-Kobayashi-Maskawa matrix elements, can have branching ratios of $\mathcal{O}(10^{-5})$. This large branching ratio could be observed at the running B factories to detect Z_s particles containing a strange quark. We also predict large branching ratios of the Z and Z_c ($\bar{c}c\bar{c}D$, $D = u, d, s$) particle production rates in nonleptonic B_c decays and radiative B decays. Measurements of these decays at the ongoing B factories and the forthcoming Large Hadron Collider-b experiments are helpful to clarify the mysterious Z particles.

DOI: 10.1103/PhysRevD.77.054001 PACS numbers: 13.25.Gv, 14.40.Gx

I. INTRODUCTION

Recently, there are many exciting discoveries on new hadron states especially in the hidden-charm sector. Among these discoveries, the most intriguing one is the new relatively narrow peak named $Z(4430)$ found by the Belle Collaboration in the invariant mass spectrum of $\pi\psi'$ in the decay mode $B \to K\pi\psi'$ [1]. There is a large branching fraction for the following decay chain:

$$\mathcal{BR}(\bar{B}^0 \to K^- Z^+(4430)) \times \mathcal{BR}(Z^+(4430) \to \pi^+ \psi') = (4.1 \pm 1.0(\text{stat}) \pm 1.3(\text{syst})) \times 10^{-5}. \quad (1)$$

Mass and width of this particle are measured as

$$m_Z = (4433 \pm 4 \pm 1)\ \text{MeV}; \qquad \Gamma_Z = (44^{+17+30}_{-13-11})\ \text{MeV}. \quad (2)$$

The most prominent characteristic is that it is electrically charged, that is to say, this new particle can not be described as an ordinary charmonium state or a charmonium-like state such as $\bar{c}cg$. On the other hand, this particle can decay to $\pi^+\psi'$ with a large rate through strong interactions, so it involves at least four quarks $c\bar{c}u\bar{d}$, though there is not any further detailed information on its inner dynamics at present.

In order to elucidate this particle, many theoretical studies [2–8] have been put forward. This meson could be viewed as a genuine tetraquark state with diquark–antidiquark $[cu][\bar{c}\,\bar{d}]$ content which has a large rate to $\pi\psi'$ [3]. Moreover based on QCD-string, two different four-quark descriptions are proposed in Ref. [6]: one can be reduced to the ordinary diquark-diquark picture and the other one can not. Besides this kind of explanation, it has also been identified as the resonance of $D_1(D_1')D^*$ [2,4] as its mass is close to the thresholds of $D^*(2010)D_1(2420)$ and $D^*(2010)D_1'(2430)$. Within this picture, the authors in Ref. [4] explored the production of $\pi\psi$ and $\pi\psi'$. The short-distance contribution to $Z \to \pi\psi(\psi')$ is neglected and the main contribution is from long distance rescattering effect via D^*D_1. With proper parameters, they can successfully explain the much larger production rate of $\pi\psi'$ than that of $\pi\psi$. In Ref. [5], Bugg took this meson as a $D^*(2010)\bar{D}(2420)$ threshold cusp. Recently, Qiao also tried to explain this meson with the baryonium picture [7]. Using the technique of QCD sum rules, Lee *et al.* calculated the masses of this particle and its strange partner Z_s in Ref. [8].

Whether or not these scenarios describe the true dynamics of $Z(4430)$, this strange meson indeed plays an important role in the charmonium spectroscopy. In the present paper, we do not intend to give an explanation of this meson's structure, but we want to analyze its partners within SU(3) symmetry: the octet to which the meson $Z(4430)$ belongs and the corresponding singlet meson. Up to now, there is no experimental information on these mesons except $Z^{\pm}$. The decays of B meson provide a firm potential in searching for these exotic mesons [9,10], just like the observed decay channel $B \to KZ \to K\pi\psi'$. We will investigate the possibilities to detect these Z mesons in $B_q(q = u, d, s, c)$ decays. In doing this, we will analyze decay amplitudes with the assumption of SU(3) flavor symmetry: to construct an effective Hamiltonian using flavor SU(3) meson matrices. The decay amplitudes can also be studied by using Feynmann diagrams. In the discussion of Z production with the graphic technique, we only consider short-distance contributions and neglect soft final state interactions. Specifically, the considered decays are divided into three categories: Cabibbo-Kobayashi-Maskawa (CKM) allowed nonleptonic decays; CKM suppressed nonleptonic decays; radiative decays. The first kind of decays have similar branching ratios with the observed $\bar{B}^0 \to K^-\pi^+\psi'$, while the second type of decays is suppressed by about one order in magnitude and we will show that the running B factories could hardly detect this kind of decays. Radiative B decay is a natural filter to exclude the 0-spin mesons and furthermore this kind of process may go through with a sizable branching ratio.

In the next section, we will analyze the octet of Z meson within flavor SU(3) symmetry and try to estimate their masses. We will construct the effective Hamiltonian using meson matrices and then use them to study the production rates of Z mesons in B decays. In Sec. III, we will introduce Z_c meson which consists of three charm quarks, together with a brief discussion on its production in B_c decays. We will summarize this paper in the last section.

II. THE OCTET AND THE SINGLET

Just as stated above, $Z(4430)$ involves at least four quarks in the constituent quark model, and there is an octet which $Z(4430)$ belongs to in flavor SU(3) symmetry. Generally, we can deduce the particles in this octet using group theory: these particles, under the names $Z^\pm$, Z^0, $Z_s^\pm$, Z_s^0, $\bar{Z}_s^0$, and Z_8, are shown in Fig. 1. Besides, there exists one singlet meson called Z_1. In the constituent quark model, quark contents of these mesons are listed by

$$\begin{aligned} &Z^+ = c\bar{c}u\bar{d}; \quad Z^0 = \frac{1}{\sqrt{2}}c\bar{c}(u\bar{u} - d\bar{d}); \quad Z^- = c\bar{c}d\bar{u}; \\ &Z_s^+ = c\bar{c}u\bar{s}; \quad Z_s^- = c\bar{c}s\bar{u}; \quad Z_s^0 = c\bar{c}d\bar{s}; \quad \bar{Z}_s^0 = c\bar{c}s\bar{d}; \\ &Z_8 = \frac{1}{\sqrt{6}}c\bar{c}(u\bar{u} + d\bar{d} - 2s\bar{s}); \quad Z_1 = \frac{1}{\sqrt{3}}c\bar{c}(u\bar{u} + d\bar{d} + s\bar{s}). \end{aligned} \tag{3}$$

In reality, the s quark is slightly heavier than the u, d quark which is one of the origins for SU(3) symmetry breaking. Accordingly, the singlet Z_1 can mix with the eighth component of the octet Z_8, in analogy with η and η'. Physical particles, named Z_α and Z_β, are mixtures of them and can be expressed as

$$\begin{pmatrix} Z_\alpha \\ Z_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Z_8 \\ Z_1 \end{pmatrix}. \tag{4}$$

The mixing angle θ can be determined through measuring decays of these two particles in the future. For simplicity,

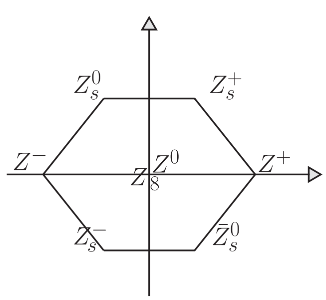

FIG. 1. Weight diagram for Z meson octet.

we will assume the mixing is ideal, i.e. $\theta = 54.7°$. In this case, the quark contents are

$$Z_\alpha = \frac{1}{\sqrt{2}}c\bar{c}(u\bar{u} + d\bar{d}), \qquad Z_\beta = c\bar{c}s\bar{s}. \tag{5}$$

All together, one can use the following meson matrix to describe these mesons:

$$Z = \begin{pmatrix} \frac{Z^0}{\sqrt{2}} + \frac{Z_8}{\sqrt{6}} & Z^+ & Z_s^+ \\ Z^- & -\frac{Z^0}{\sqrt{2}} + \frac{Z_8}{\sqrt{6}} & Z_s^0 \\ Z_s^- & \bar{Z}_s^0 & -\sqrt{\frac{2}{3}}Z_8 \end{pmatrix} + \frac{Z_1}{\sqrt{3}}\mathbf{1}. \tag{6}$$

With the quark contents given in the above, we are ready to estimate masses of these particles. Isospin analysis predicts the equal masses for the four mesons with neither open nor hidden strangeness: $Z^\pm$, Z^0, Z_α. For the mesons with a strange quark, the mass differences between the lighter u, d quarks and the heavier s quark are required. One can compare masses of D^* and D_s^* to get some information: the mass of D_s^* is 100 MeV larger than that of D^*. In the heavy quark limit $m_c \to \infty$, the light system will not be affected by different heavy quark systems; thus we can simply assume a similar difference for Z mesons which predict the mass of Z_s around 4533 MeV. Because the mass of the newly observed Z meson is not far from the threshold of $D^*(2010)D_1(2420)$, the Z^- meson is regarded as the resonance of $D^*\bar{D}_1(2420)$ [2]. Under this mechanism, we could give more precise predictions on the masses for other Z mesons using experimental results for the D^* and D_1 mesons. Our results are listed in Table I and uncertainties in this table are from that of masses of the charmed mesons. In the heavy quark limit, mesons with the same light system can be related to each other. But if the Z particles are viewed as tetraquark states, the effective strange quark mass in Z could be different from that in the usual mesons as the light systems in the two kinds of particles are different. If Z mesons are described as molecules, probably they would not belong to a full SU(3) nonet and the predicted masses may not be suitable. Currently, there is no better solution and we will use this assumption in the present study. The recent QCD sum rule study predicts the mass by [8]

$$m_{Z_s} = (4.70 \pm 0.06)\ \text{GeV}, \tag{7}$$

which is above the $D_s^*D_1$ and D^*D_{s1} threshold by about 160 MeV. More experimental studies are required to test this description.

Experimentalists have observed the Z particle through the $B \to ZK$ with $Z \to \pi\psi'$. Assuming S-wave decay for the Z meson, the quantum numbers can be determined as $J^{PC} = 1^{+-}$ [3]. In order to detect the other Z mesons, experimentalists will choose the proper final states to reconstruct them, thus the predictions on Z's strong decays are required. Using the flavor SU(3) symmetry and $Z \to \pi\psi'$, we also list the strong decays of other Z mesons in

TABLE I. Z meson and its mass.

Meson	Constituent meson	Mass (MeV)	Decay mode
Z^+, Z^-, Z^0, Z_α	$D^*(2010)\bar{D}_1(2420)$	4432.3 ± 1.7	$\psi'\pi/\eta(\eta')$, $\eta_c(2S)\rho/\omega$
Z_s^+, Z_s^-, Z_s^0, $\bar{Z}_s^0$	$D_s^*(2112)\bar{D}_1(2420)/D^*(2010)\bar{D}_{s1}(2536)$	$4534.3 \pm 1.9/4535.35 \pm 1.0$	$\psi' K$, $\eta_c(2S)K^*$
Z_β	$D_s^*(2112)\bar{D}_{s1}(2536)$	4647.35 ± 1.2	$\psi'\eta(\eta')$, $\eta_c(2S)\phi$

Table I. With the assumption $J^{PC} = 1^{+-}$, another kind of possible decay modes is $Z \to \eta_c(2S)V$ [3], where V denotes a light vector meson.

In order to explore the production in B decays, one can construct the effective Hamiltonian at hadron level using meson matrices [11]. In the following, to construct the related effective Hamiltonian, we will assume the flavor SU(3) symmetry. In $B_{u,d,s}$ decays, the initial state $B = (B^-, \bar{B}^0, \bar{B}_s^0)$ forms an SU(3) antitriplet. The transition at quark level is either $b \to c\bar{c}s$ or $b \to c\bar{c}d$,[1], which is described by the effective electroweak Hamiltonian:

$$H = \frac{G_F}{\sqrt{2}} V_{cb} V_{cD}^* [C_1 (\bar{c}_\alpha b_\beta)_{V-A} (\bar{D}_\beta c_\alpha)_{V-A} + C_2 (\bar{c}_\alpha b_\alpha)_{V-A} (\bar{D}_\beta c_\beta)_{V-A}] + \text{H.c.}, \quad (8)$$

where $D = d, s$. α and β are color indices. The transition $b \to c\bar{c}s$ is CKM favored: $V_{cb}V_{cs}^* \sim 1$, while the $b \to c\bar{c}d$ transition is suppressed by $|V_{cd}^*/V_{cs}^*| = \lambda = 0.23$. To construct the effective Hamiltonian at hadron level, only the flavor structures need to be concerned. The effective electroweak Hamiltonian given in Eq. (8) can also be written as an SU(3) triplet: $H^i (i = 1(u), 2(d), 3(s))$, where the only nonzero elements are $H^3 = 1$ for CKM favored decays $b \to c\bar{c}s$, and $H^2 = 1$ for CKM suppressed channels $b \to c\bar{c}d$. The final state mesons can be described by two nonet matrices: Z and M. The effective Hamiltonian at hadron level could be constructed as

$$\mathcal{H} = \mathcal{A}_3 B_i H^i Z_l^k M_k^l + \mathcal{B}_3 B_i H^j Z_l^i M_j^l + \mathcal{C}_3 B_i H^j Z_j^k M_k^i + \mathcal{D}_3 B_i H^j Z_j^i M_l^l + \mathcal{E}_3 B_i H^j Z_l^l M_j^i, \quad (9)$$

where the upper index labels rows and the lower labels columns.

The above effective Hamiltonian can be related to Feynmann diagrams with the one-to-one correspondence and the lowest order diagrams are given in Fig. 2. The second term in Eq. (9) corresponds to the second diagram in Fig. 2 (called the Z-recoiling diagram) in which the spectator light quark in the B meson enters into the heavy Z meson. If the spectator quark goes to the light meson, we call this kind of diagram (the third one in Fig. 2) the Z-emission diagram which corresponds to the third term in the effective Hamiltonian. In order to estimate relative sizes of these terms, we have to analyze diagrams at quark level. Final state mesons move very slowly and thus the gluon generating the $q\bar{q}$ quark pair is soft: $\alpha_s \sim \mathcal{O}(1)$. Thus after integrating out high energy scales, decay amplitudes can be expressed as matrix elements of a soft four-quark operator between initial and final states. The first term in Eq. (9) corresponds to the annihilation diagram (the first one in Fig. 2), as flavor indices of B and H in this term are contracted with each other. This kind of diagram is expected to be suppressed in two-body nonleptonic B decays. But here since the gluons are soft, decay amplitudes can also be expressed as time-ordered products of a soft four-quark operator and the $\mathcal{O}(1)$ interaction Hamiltonian which contains only soft fields; thus this kind of contribution is comparable with contributions from the second and third terms in Eq. (9). For SU(3) flavor singlet mesons η_1 and Z_1, there are additional contributions which are given by the last two terms in Eq. (9). One kind of typical Feynmann diagram is also shown in Fig. 2 as the last two diagrams, and it is the contribution from the higher Fock states of η_1 and Z_1. Even in charmless two-body $B \to K(\pi)\eta(\eta')$ decays [12], this kind of gluonic contribution is sizable. Here we do not have any implication and thus one can not neglect it with any *a priori*.

With the effective Hamiltonian given in Eq. (9), we give the decay amplitudes for the first kind of nonleptonic $B_{u,d,s}$ decay channels in Table II. These decays are induced by the CKM allowed transition $b \to c\bar{c}s$ and go through with a large decay rate (typically the same order with the

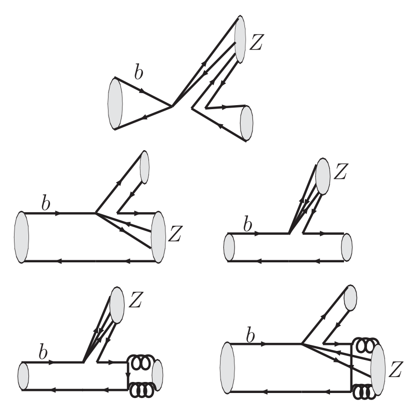

FIG. 2. Typical Feynman diagrams: annihilation (first row), emission (second row), and gluonic diagrams (third row) of Z meson production in B decays.

[1]If the $\bar{c}c$ quark pair is generated from the QCD vacuum rather than directly produced by the four-quark operator, this kind of contribution is expected to be suppressed by $\alpha_s(2m_c)$ since there is at least one hard gluon required to produce the $\bar{c}c$ quark pair.

TABLE II. SU(3) decomposition of $\Delta S = 1$ $B_{u,d,s}$ decays, whose decay amplitudes are proportional to $V_{cb}V_{cs}^*$.

Mode	$\mathcal{A}_3$	$\mathcal{B}_3$	$\mathcal{C}_3$	$\mathcal{D}_3$	$\mathcal{E}_3$
$B^- \to Z^0 K^-$	0	$1/\sqrt{2}$	0	0	0
$B^- \to Z^- \bar{K}^0$	0	1	0	0	0
$B^- \to Z_s^- \pi^0$	0	0	$1/\sqrt{2}$	0	0
$B^- \to \bar{Z}_s^0 \pi^-$	0	0	1	0	0
$B^- \to Z_8 K^-$	0	$1/\sqrt{6}$	$-\sqrt{2/3}$	0	0
$B^- \to Z_1 K^-$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	0	$\sqrt{3}$
$B^- \to Z_s^- \eta_8$	0	$-\sqrt{2/3}$	$1/\sqrt{6}$	0	0
$B^- \to Z_s^- \eta_1$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	$\sqrt{3}$	0
$\bar{B}^0 \to Z^+ K^-$	0	1	0	0	0
$\bar{B}^0 \to Z^0 \bar{K}^0$	0	$-1/\sqrt{2}$	0	0	0
$\bar{B}^0 \to Z_s^- \pi^+$	0	0	1	0	0
$\bar{B}^0 \to \bar{Z}_s^0 \pi^0$	0	0	$-1/\sqrt{2}$	0	0
$\bar{B}^0 \to Z_8 \bar{K}^0$	0	$1/\sqrt{6}$	$-\sqrt{2/3}$	0	0
$\bar{B}^0 \to Z_1 \bar{K}^0$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	0	$\sqrt{3}$
$\bar{B}^0 \to \bar{Z}_s^0 \eta_8$	0	$-\sqrt{2/3}$	$1/\sqrt{6}$	0	0
$\bar{B}^0 \to \bar{Z}_s^0 \eta_1$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	$\sqrt{3}$	0
$\bar{B}_s^0 \to Z_s^+ K^-$	1	1	0	0	0
$\bar{B}_s^0 \to Z_s^0 \bar{K}^0$	1	1	0	0	0
$\bar{B}_s^0 \to Z_s^- K^+$	1	0	1	0	0
$\bar{B}_s^0 \to \bar{Z}_s^0 K^0$	1	0	1	0	0
$\bar{B}_s^0 \to Z^+ \pi^-$	1	0	0	0	0
$\bar{B}_s^0 \to Z^- \pi^+$	1	0	0	0	0
$\bar{B}_s^0 \to Z^0 \pi^0$	1	0	0	0	0
$\bar{B}_s^0 \to Z_8 \eta_1$	0	$-\sqrt{2}/3$	$-\sqrt{2}/3$	$-\sqrt{2}$	0
$\bar{B}_s^0 \to Z_1 \eta_8$	0	$-\sqrt{2}/3$	$-\sqrt{2}/3$	0	$-\sqrt{2}$
$\bar{B}_s^0 \to Z_8 \eta_8$	1	2/3	2/3	0	0
$\bar{B}_s^0 \to Z_1 \eta_1$	1	1/3	1/3	1	1

observed $\bar{B}^0 \to K^- \pi^+ \psi'$). The flavor SU(3) symmetry implies the following relations for $b \to c\bar{c}s$ decays:

$$2\mathcal{BR}(B^- \to Z^0 K^-) = \mathcal{BR}(B^- \to Z^- \bar{K}^0) = \mathcal{BR}(\bar{B}^0 \to Z^+ K^-) = 2\mathcal{BR}(\bar{B}^0 \to Z^0 \bar{K}^0), \quad (10)$$

$$2\mathcal{BR}(B^- \to Z_s^- \pi^0) = \mathcal{BR}(B^- \to \bar{Z}_s^0 \pi^-) = \mathcal{BR}(\bar{B}^0 \to Z_s^- \pi^+) = 2\mathcal{BR}(\bar{B}^0 \to \bar{Z}_s^0 \pi^0), \quad (11)$$

$$\mathcal{BR}(B^- \to Z_\alpha K^-) = \mathcal{BR}(\bar{B}^0 \to Z_\alpha \bar{K}^0), \quad \mathcal{BR}(B^- \to Z_\beta K^-) = \mathcal{BR}(\bar{B}^0 \to Z_\beta \bar{K}^0), \quad (12)$$

$$\mathcal{BR}(B^- \to Z_s^- \eta) = \mathcal{BR}(\bar{B}^0 \to \bar{Z}_s^0 \eta), \quad (13)$$

$$\mathcal{BR}(\bar{B}_s^0 \to Z_s^+ K^-) = \mathcal{BR}(\bar{B}_s^0 \to Z_s^0 \bar{K}^0), \quad \mathcal{BR}(\bar{B}_s^0 \to Z_s^- K^+) = \mathcal{BR}(\bar{B}_s^0 \to \bar{Z}_s^0 K^0), \quad (14)$$

$$\mathcal{BR}(\bar{B}_s^0 \to Z^+ \pi^-) = \mathcal{BR}(\bar{B}_s^0 \to Z^- \pi^+) = \mathcal{BR}(\bar{B}_s^0 \to Z^0 \pi^0), \quad (15)$$

where mass differences and lifetime differences of B mesons are neglected which can not produce large corrections. Although all of these decays are expected to go through with large branching fractions, decay rates may differ from each other for distinct coefficients. Two of the decays in the first line have been observed experimentally, while the possibility to observe the other two channels is a little smaller as the daughter meson π^0 from Z^0 is relatively more difficult to measure. The decays in the second line are contributed from the third term of the effective Hamiltonian given in Eq. (9), which should also have similar production rates. Among these four channels, $\bar{B}^0 \to Z_s^- \pi^+$ and $B^- \to \bar{Z}_s^0 \pi^-$ can have large branching ratios and the final states ($K^- \psi' \pi^+$ or $K_S \psi' \pi^+$) are easily to be measured on the experimental side. Thus measurements of the $K\psi'$ invariant mass distribution in these two channels are helpful to detect the Z_s particles and determine relative sizes of $\mathcal{B}_3$ and $\mathcal{C}_3$. The other B decays are less possible to be measured in the running B factories as either π^0 or η is produced in the final state. The forthcoming LHC-b experiments and super-B factories can measure these decays, together with the $\bar{B}_s^0$ decays.

For $\bar{B}^0 \to K^- Z^+$, the heavy b quark decays into $c\bar{c}s$, and $q\bar{q}$ is produced from a vacuum. Subsequently, $c\bar{c}$, q, and the spectator $\bar{u}$ can be transferred into Z, and the quarks left form a kaon. The other Z states can also be produced by selecting a different quark pair $q\bar{q}$ or changing the s quark by d quark. We give the decay amplitudes for nonleptonic $B_{u,d,s}$ decay channels induced by $b \to c\bar{c}d$ transition in Table III. These decays are suppressed by CKM matrix elements $|V_{cd}/V_{cs}|^2$. $B^- \to Z_s^- K^0$ is one example of this kind of decay and the product branching ratio is

$$\mathcal{BR}[B^- \to Z_s^- K^0] \times \mathcal{BR}[Z_s^- \to K^- \psi'] = \left|\frac{V_{cd}}{V_{cs}}\right|^2 \times \mathcal{BR}[\bar{B}^0 \to Z^+(4430) K^-] \times \mathcal{BR}[Z^+(4430) \to \pi^+ \psi'] = (2.3 \pm 0.6 \pm 0.7) \times 10^{-6}, \quad (16)$$

where $|V_{cd}| = 0.23$ and $|V_{cs}| = 0.957$ [13]. The uncertainties are from the experimental results for $\mathcal{BR}[\bar{B}^0 \to Z^+(4430) K^-] \times \mathcal{BR}[Z^+(4430) \to \pi^+ \psi']$. In the above calculation, mass differences and lifetime differences are neglected again. From the branching ratio for this decay chain, we can see that this kind of process receives strong suppression. Furthermore, the detection of K_S is more difficult than K^-; thus it could hardly be measured at the present two B factories. The relations for the $b \to c\bar{c}d$ decay can be derived similarly using the effective Hamiltonian which is also useful in searching for the Z mesons:

TABLE III. SU(3) decomposition of $\Delta S = 0$ $B_{u,d,s}$ decays, whose decay amplitudes are proportional to $V_{cb}V_{cd}^*$.

Mode	$\mathcal{A}_3$	$\mathcal{B}_3$	$\mathcal{C}_3$	$\mathcal{D}_3$	$\mathcal{E}_3$
$B^- \to Z^0\pi^-$	0	$1/\sqrt{2}$	$-1/\sqrt{2}$	0	0
$B^- \to Z^-\pi^0$	0	$-1/\sqrt{2}$	$1/\sqrt{2}$	0	0
$B^- \to Z_s^- K^0$	0	1	0	0	0
$B^- \to Z_s^0 K^-$	0	0	1	0	0
$B^- \to Z_8\pi^-$	0	$1/\sqrt{6}$	$1/\sqrt{6}$	0	0
$B^- \to Z_1\pi^-$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	0	$\sqrt{3}$
$B^- \to Z^-\eta_8$	0	$1/\sqrt{6}$	$1/\sqrt{6}$	0	0
$B^- \to Z^-\eta_1$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	$\sqrt{3}$	0
$\bar{B}^0 \to Z^+\pi^-$	1	1	0	0	0
$\bar{B}^0 \to Z^-\pi^+$	1	0	1	0	0
$\bar{B}^0 \to Z^0\pi^0$	1	1/2	1/2	0	0
$\bar{B}^0 \to Z_s^+ K^-$	1	0	0	0	0
$\bar{B}^0 \to Z_s^0\bar{K}^0$	1	0	1	0	0
$\bar{B}^0 \to Z_s^- K^+$	1	0	0	0	0
$\bar{B}^0 \to \bar{Z}_s^0 K^0$	1	1	0	0	0
$\bar{B}^0 \to Z_8\pi^0$	0	$-1/2\sqrt{3}$	$-1/2\sqrt{3}$	0	0
$\bar{B}^0 \to Z_1\pi^0$	0	$-1/\sqrt{6}$	$-1/\sqrt{6}$	0	$-\sqrt{3/2}$
$\bar{B}^0 \to Z^0\eta_8$	0	$-1/2\sqrt{3}$	$-1/2\sqrt{3}$	0	0
$\bar{B}^0 \to Z^0\eta_1$	0	$-1/\sqrt{6}$	$-1/\sqrt{6}$	$-\sqrt{3/2}$	0
$\bar{B}^0 \to Z_8\eta_8$	1	1/6	1/6	0	0
$\bar{B}^0 \to Z_8\eta_1$	0	$1/3\sqrt{2}$	$1/3\sqrt{2}$	$1/\sqrt{2}$	0
$\bar{B}^0 \to Z_1\eta_8$	0	$1/3\sqrt{2}$	$1/3\sqrt{2}$	0	$1/\sqrt{2}$
$\bar{B}^0 \to Z_1\eta_1$	1	1/3	1/3	1	1
$\bar{B}_s^0 \to Z_s^+\pi^-$	0	1	0	0	0
$\bar{B}_s^0 \to Z_s^0\pi^0$	0	$-1/\sqrt{2}$	0	0	0
$\bar{B}_s^0 \to Z^- K^+$	0	0	1	0	0
$\bar{B}_s^0 \to Z^0 K^0$	0	0	$-1/\sqrt{2}$	0	0
$\bar{B}_s^0 \to Z_8 K^0$	0	$-\sqrt{2/3}$	$1/\sqrt{6}$	0	0
$\bar{B}_s^0 \to Z_1 K^0$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	0	$\sqrt{3}$
$\bar{B}_s^0 \to Z_s^0\eta_8$	0	$1/\sqrt{6}$	$-\sqrt{2/3}$	0	0
$\bar{B}_s^0 \to Z_s^0\eta_1$	0	$1/\sqrt{3}$	$1/\sqrt{3}$	$\sqrt{3}$	0

$$\mathcal{BR}(B^- \to Z_s^- K^0) = \mathcal{BR}(\bar{B}_s^0 \to Z_s^+\pi^-) = 2\mathcal{BR}(\bar{B}_s^0 \to Z_s^0\pi^0), \quad (17)$$

$$\mathcal{BR}(B^- \to Z_s^0 K^-) = \mathcal{BR}(\bar{B}_s^0 \to Z^- K^+) = 2\mathcal{BR}(\bar{B}_s^0 \to Z^0 K^0), \quad (18)$$

$$\mathcal{BR}(B^- \to Z^-\pi^0) = \mathcal{BR}(B^- \to Z^0\pi^-), \quad (19)$$

$$\mathcal{BR}(\bar{B}^0 \to Z^+\pi^-) = \mathcal{BR}(\bar{B}^0 \to \bar{Z}_s^0 K^0), \quad \mathcal{BR}(\bar{B}^0 \to Z^-\pi^+) = \mathcal{BR}(\bar{B}^0 \to Z_s^0\bar{K}^0), \quad (20)$$

$$\mathcal{BR}(B^- \to Z_{\alpha,\beta}\pi^-) = 2\mathcal{BR}(\bar{B}^0 \to \bar{Z}_{\alpha,\beta}\pi^0), \quad \mathcal{BR}(B^- \to Z^-\eta(\eta')) = 2\mathcal{BR}(\bar{B}^0 \to Z^0\eta(\eta')). \quad (21)$$

As pointed out in Ref. [14], the study of charmoniumlike states production in B_c decays is easier. Here we also consider the Z(4430) particle production in B_c decays. In this case, the spectator is a $\bar{c}$ quark; thus the initial state is very simple: a singlet of the flavor SU(3) group. But the effective electroweak Hamiltonian can form an octet: $3 \otimes \bar{3} = 8 \oplus 1$. The effective Hamiltonian at hadron level can be written by

$$\mathcal{H} = \mathcal{A}_8 B H^i_j Z^j_l M^l_i + \mathcal{B}_8 B H^i_j Z^k_i M^j_k + \mathcal{C}_8 B H^i_j M^j_i Z^k_k + \mathcal{D}_8 B H^i_j Z^j_i M^l_l, \quad (22)$$

where the nonzero elements of the transition Hamiltonian are $H^2_1 = 1$ for CKM allowed channels $b \to c\bar{u}d$ and $H^3_1 = 1$ for CKM suppressed channels $b \to c\bar{u}d$ with a factor V_{us}^*/V_{ud}^*. The corresponding Feynmann diagrams are given in Fig. 3. The coefficients for distinct contributions are given in Table IV. The CKM matrix element for the decay channels induced by $b \to c\bar{u}d$ is $V_{cb}V_{ud}^*$, which is in the same order with that of $B \to KZ(4430)$: $V_{cb}V_{cs}^*$. Thus without any other suppressions, these B_c decays also have similar branching ratios $[\mathcal{O}(10^{-5})]$ with $\bar{B}^0 \to K^- Z^+ \to K^-\pi^+\psi'$. The decays in the second part of

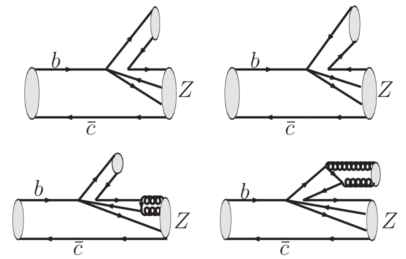

FIG. 3. Leading order Feynman diagrams of Z meson production in B_c decays.

TABLE IV. SU(3) decomposition of B_c induced by $b \to c\bar{u}d$ (the first part) and $b \to c\bar{u}s$ transitions (the second part).

Mode	$\mathcal{A}_3$	$\mathcal{B}_3$	$\mathcal{C}_3$	$\mathcal{D}_3$
$B_c^- \to Z_s^0 K^-$	0	1	0	0
$B_c^- \to Z_s^- K^0$	1	0	0	0
$B_c^- \to Z^0\pi^-$	$1/\sqrt{2}$	$-1/\sqrt{2}$	0	0
$B_c^- \to Z^-\pi^0$	$-1/\sqrt{2}$	$1/\sqrt{2}$	0	0
$B_c^- \to Z_8\pi^-$	$1/\sqrt{6}$	$1/\sqrt{6}$	0	0
$B_c^- \to Z_1\pi^-$	$1/\sqrt{3}$	$1/\sqrt{3}$	$\sqrt{3}$	0
$B_c^- \to Z^-\eta_8$	$1/\sqrt{6}$	$1/\sqrt{6}$	0	0
$B_c^- \to Z^-\eta_1$	$1/\sqrt{3}$	$1/\sqrt{3}$	0	$\sqrt{3}$
Mode	$\mathcal{A}_3$	$\mathcal{B}_3$	$\mathcal{C}_3$	$\mathcal{D}_3$
$B_c^- \to Z^0 K^-$	$1/\sqrt{2}$	0	0	0
$B_c^- \to Z^-\bar{K}^0$	1	0	0	0
$B_c^- \to \bar{Z}_s^0\pi^-$	0	1	0	0
$B_c^- \to Z_s^-\pi^0$	0	$1/\sqrt{2}$	0	0
$B_c^- \to Z_8 K^-$	$1/\sqrt{6}$	$-\sqrt{2/3}$	0	0
$B_c^- \to Z_1 K^-$	$1/\sqrt{3}$	$1/\sqrt{3}$	$\sqrt{3}$	0
$B_c^- \to Z_s^-\eta_8$	$-\sqrt{2/3}$	$1/\sqrt{6}$	0	0
$B_c^- \to Z_s^-\eta_1$	$1/\sqrt{3}$	$1/\sqrt{3}$	0	$\sqrt{3}$

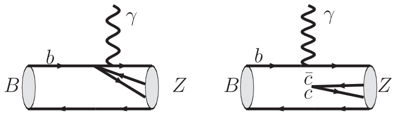

FIG. 4. Z meson production via radiative decays. The right diagram gives a smaller contribution as at least one hard gluon is required.

Table IV are suppressed by $(V_{us}^*/V_{ud}^*)^2$, which are expected to have smaller decay rates $[\mathcal{O}(10^{-6})]$. Furthermore, the SU(3) symmetry implies the following relations:

$$\mathcal{BR}(\bar{B}_c^- \to Z^0\pi^-) = \mathcal{BR}(\bar{B}_c^- \to Z^-\pi^0), \tag{23}$$

$$2\mathcal{BR}(\bar{B}_c^- \to Z^0K^-) = \mathcal{BR}(\bar{B}_c^- \to Z^-\bar{K}^0), \tag{24}$$

$$2\mathcal{BR}(\bar{B}_c^- \to Z_s^-\pi^0) = \mathcal{BR}(\bar{B}_c^- \to \bar{Z}_s^0\pi^-). \tag{25}$$

Besides nonleptonic B decays, Z particles can also be produced in radiative decays, as Fig. 4 shows. Two-body radiative decays can serve as a natural filter to exclude spin-0 candidates of Z particles, as the photon can only be transversely polarized. But in order to predict the production rates, one has to know $B \to Z$ transition form factors. In the second diagram of Fig. 4, in order to generate the $\bar{c}c$, we require at least one hard gluon which will suppress the contribution from this diagram. Naïvely thinking, the first diagram will also be suppressed by the off-shell c quark propagator, but since the emitted photon is not energetic (the total energy release is only about 0.8 GeV), the off-shellness is not large. This may imply the following radiative B decays could go through with considerable rates:

$$\begin{aligned} &B^- \to Z_s^-\gamma, \qquad \bar{B}^0 \to \bar{Z}_s^0\gamma, \\ &\bar{B}_s^0 \to Z_8(Z_1)\gamma, \qquad \bar{B}_c \to Z^-\gamma. \end{aligned} \tag{26}$$

III. Z_c PARTICLE

In the above, we have utilized the flavor SU(3) symmetry for light quarks in Z mesons. One can also replace one or two heavy c quarks by heavier b quarks which can predict Z_b and Z_{bb} mesons [15]. Another attempt is to replace a light quark by a heavy c quark. With this replacement, we obtain three Z_c states which contain three heavy quarks and a light quark: $\bar{c}c\bar{c}u$, $\bar{c}c\bar{c}d$, and $\bar{c}c\bar{c}s$, together with their charge conjugates. We have to confess that this replacement may change the internal dynamics, but here we assume the same dynamics with Z. In this case, the masses can be obtained by using mass differences of c and u, d, s quarks deriving from masses of ψ and $D^*(D_s^*)$. The rough predictions for masses are around 5520 and 5630 MeV. If these mesons are viewed as the resonance of ψ and $D_1(D_{s1})$, their masses could be predicted as (5519.2 ± 1.3) MeV, (5519.2 ± 1.3) MeV, and (5632.3 ± 0.6) MeV.

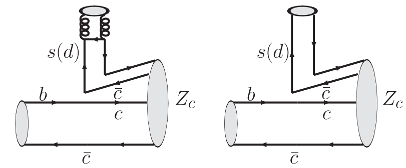

FIG. 5. Leading order Feynman diagrams of Z_c meson production in nonleptonic B_c decays.

Because of the large mass of Z_c, these particles only appear in B_c meson decays. The corresponding effective Hamiltonian responsible for nonleptonic decays is

$$\mathcal{H} = \mathcal{A}_3 BH^i Z_i M_k^k + \mathcal{B}_3 BH^i Z_j M_i^j, \tag{27}$$

where the first contribution $\mathcal{A}_3$ comes from the gluonic diagram shown as the first one in Fig. 5; while the second term $\mathcal{B}_3$ comes from the Z-recoiling diagram shown as the second one in Fig. 5. These two contributions give the following amplitudes for 8 decays:

$$A(\bar{B}_c \to Z(\bar{c}c\bar{c}u)K^-) = A(\bar{B}_c \to Z(\bar{c}c\bar{c}d)\bar{K}^0) = \mathcal{B}_3, \tag{28}$$

$$A(\bar{B}_c \to Z(\bar{c}c\bar{c}s)\eta_8) = -\sqrt{\frac{2}{3}}\mathcal{B}_3, \tag{29}$$

$$A(\bar{B}_c \to Z(\bar{c}c\bar{c}s)\eta_1) = \sqrt{3}\mathcal{A}_3 + \frac{1}{\sqrt{3}}\mathcal{B}_3, \tag{30}$$

$$\begin{aligned} A(\bar{B}_c \to Z(\bar{c}c\bar{c}u)\pi^-) &= -\sqrt{2}A(\bar{B}_c \to Z(\bar{c}c\bar{c}d)\pi^0) \\ &= A(\bar{B}_c \to Z(\bar{c}c\bar{c}s)K^0) = \mathcal{B}_3, \end{aligned} \tag{31}$$

$$A(\bar{B}_c \to Z(\bar{c}c\bar{c}d)\eta_8) = \frac{1}{\sqrt{6}}\mathcal{B}_3, \tag{32}$$

$$A(\bar{B}_c \to Z(\bar{c}c\bar{c}d)\eta_1) = \sqrt{3}\mathcal{A}_3 + \frac{1}{\sqrt{3}}\mathcal{B}_3. \tag{33}$$

The first 4 decay channels shown in Eqs. (28)–(30) are induced by $b \to c\bar{c}s$ at quark level and thus have branching ratios of order $\mathcal{O}(10^{-5})$, while the other decays shown in Eqs. (31)–(33) are suppressed by $|V_{cd}^*/V_{cs}^*|^2$, which have smaller decay rates $[\mathcal{O}(10^{-6})]$.

IV. SUMMARY

The Belle Collaboration has reported a resonance named $Z(4430)$, which consists of at least four quarks in constituent quark model. In this paper, we analyze the octet to which this Z meson belongs and the corresponding singlet meson. Using the picture that the Z mesons are the resonances of D^* and D_1 mesons, we estimate the masses of these mesons. We investigate the production in nonleptonic $B_{u,d,s}$ decays by constructing the effective Hamiltonian using flavor SU(3) meson matrices. The transition at quark level is either $b \to c\bar{c}s$ or $b \to c\bar{c}d$, where the former one is CKM favored and the latter is suppressed by $|V_{cd}^*/V_{cs}^*|^2$. Thus the considered nonleptonic decays have either similar branching ratios with the observed decay $B^{\pm} \to Z^{\pm}\bar{K}^0$ (10^{-5}) or smaller branching ratios (10^{-6}) as shown in the text. Utilizing the SU(3) symmetry, we also obtain many relations for various decay channels. Measurements of the $K\psi'$ invariant mass distribution in $\bar{B}^0 \to Z_s^- \pi^+ \to K^-\psi'\pi^+$ and $B^- \to \bar{Z}_s^0\pi^- \to K_S\psi'\pi^-$ are helpful to detect the Z_s particles and determine the relative size of $\mathcal{B}_3$ and $\mathcal{C}_3$. We also study the production rates in nonleptonic B_c decays and radiative B decays in a similar way. Replacing a light u, d, s quark by a heavy c quark, we get three states which have three heavy quarks. The masses and the production in B_c decays are also discussed. Measurements of all these decays at the present B factories and the forthcoming LHC-b experiments will help us to clarify the new Z particles.

ACKNOWLEDGMENTS

This work is partly supported by the National Science Foundation of China under Grant Nos. 10735080, 1062525, and 10747156 and by the Foundation of Yantai University under Grant No. WL07B19. We would like to acknowledge F.-K. Guo, C.-Z. Yuan, and S. Zhou for valuable discussions.

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