Evidence for two-quark content of $f_0(980)$ in exclusive $b\to c$ decays

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(Received 26 December 2002; published 14 May 2003)

Inspired by a large decay branching ratio (BR) of $B^+\to f_0(980)K^+$ measured by Belle recently, we propose that significant evidence of the component of $n\bar{n}=(u\bar{u}+d\bar{d})/\sqrt{2}$ in $f_0(980)$ could be demonstrated in exclusive $b\to c$ decays by the observation of $f_0(980)$ in the final states $\bar{B}\to D^{0(*)}\pi^+\pi^-(KK)$ and $\bar{B}\to J/\psi\pi^+\pi^-(KK)$. We predict the BRs of $\bar{B}\to D^{0(*)}(J/\psi)f_0(980)$ to be $\mathcal{O}(10^{-4})$ $[\mathcal{O}(10^{-5})]$ while the unknown wave functions of $D^{(*)0}$ (J/ψ) are chosen to fit the observed decays of $\bar{B}\to D^{(*)0}\pi^0$ $(J/\psi K^{0(*)})$.

DOI: 10.1103/PhysRevD.67.094011 PACS number(s): 13.25.Hw, 14.40.Cs

In spite of the successful quark model and QCD theory for strong interaction, the fundamental questions on the inner structure of the lightest scalar mesons, such as $f_0(400-1200)$, $f_0(980)$, and $a_0(980)$, etc., are still uncertain, even though it has been over 30 years since $f_0(980)$ was discovered first in the phase shift analysis of elastic $\pi\pi$ scattering [1]. In addition to the interpretations of $qq\bar{q}\bar{q}$ four-quark states [2] or $K\bar{K}$ molecular states [3] or $q\bar{q}$ states [4], etc., the possibilities of gluonium states [5] and scalar glueballs [7] are also proposed. It might be oversimple to regard them as only one kind of composition.

It is suggested that in terms of $\gamma\gamma$ [5] and radiative ϕ [8,9] decays, the nature of scalar mesons can be disentangled. However, with these experiments, the conclusions such as given by Refs. [10,11] and Ref. [12] are not unique. The former prefers $q\bar{q}$ while the latter is the four-quark content. Nevertheless, according to the data of E791 [13] and Focus [14], the production of scalar mesons which are reconstructed from D and D_s decaying to three-pseudoscalar final states and mainly showing $q\bar{q}$ contents can provide us a further resolution [15]. In addition, Z_0 decay data of OPAL [16] also hint that $f_0(980)$, $f_2(1270)$, and $\phi(1020)$ have the same internal structure. Hence, the compositions of light scalar bosons should be examined further.

Recently, the decay of $B^+\to f_0(980)K^+$ with the BR product of $Br(B^+\to f_0(980)K^+)\times Br(f_0(980)\to\pi^+\pi^-)=(9.6^{+2.5+1.5+3.4}_{-2.3-1.5-0.8})\times 10^{-6}$ has been observed in Belle [17]. The observation not only displays for the first time B decay to scalar-pseudoscalar final states but also provides a chance to understand the characteristics of scalar mesons. Since the B meson is much heavier than $D_{(s)}$ mesons, in the two-body B decays, the outgoing light mesons will behave as massless particles so that the perturbative QCD (PQCD) approach [18,19], in which the corresponding bound states are expanded by Fock states, could apply. Therefore, as compared to two-parton states, the contributions of four-parton and gluonium states belong to higher Fock states. Consequently, we think that the effects of $q\bar{q}$ state are more important than those in D_s decays. In this paper, in order to further understand what the nature of $f_0(980)$ in B decays is, we take it to be composed of $q\bar{q}$ states mainly and use $|f_0(980)\rangle=\cos\phi_s|s\bar{s}\rangle+\sin\phi_s|n\bar{n}\rangle$ with $n\bar{n}=(u\bar{u}+d\bar{d})/\sqrt{2}$ to denote its flavor wave function. We note that so far ϕ_s could be $42.14^{+5.8^0}_{-7.3}$ [5] and $138°\pm 6°$ [6]. With the lowest order criterion, the effects of four-parton and gluonium states are neglected.

Inspired by the large BR of $B^+\to f_0(980)K^+$, we propose that a significant evidence of the component of $n\bar{n}$ in $f_0(980)$ could be demonstrated by exclusive $\bar{B}\to D^{(*)0}f_0(980)$ and $\bar{B}\to J/\psi f_0(980)$ processes and $f_0(980)$ could be reconstructed from the decays $\bar{B}\to D^{(*)0}\pi^+\pi^-(KK)$ and $\bar{B}\to J/\psi\pi^+\pi^-(KK)$. The results could be the complement to the three-body decays of D_s that already indicate the existence of the $s\bar{s}$ component.

It is known that the exclusive $b\to c$ decays are dominated by the tree contributions and only $(V-A)\otimes(V-A)$ four-Fermi interactions need to be considered. The difficulty in our calculations is how to determine the involving wave functions which are sensitive to the nonperturbative QCD effects and are universal objects. In the B meson case, one can fix it by $B\to PP$ processes, with P corresponding to light pseudoscalars in which the wave functions are defined in the frame of light-cone and have been derived from the QCD sum rule [20]. As to the $D^{(*)0}(J/\psi)$ wave functions, we can call for the measured BRs of color-suppressed decays $\bar{B}\to D^0\pi^0$ [21] and $\bar{B}\to J/\psi K^{(*)}$ [22]. However, it might be questionable to apply the QCD approach for ordinary PP modes to $D^{(*)}(J/\psi)$ decays because they are not light mesons anymore. In the heavy b quark limit, fortunately, the involved scales satisfy $m_b\gg m_c\gg\bar{\Lambda}$ with $m_{b(c)}$ being the mass of $b(c)$-quark and $\bar{\Lambda}=M_B-m_b$ so that the leading power effects in terms of the expansions of $\bar{\Lambda}/m_c$ and m_c/m_b could be taken as the criterion to estimate the involving processes. We will see later that not only the obtained BRs of $\bar{B}\to J/\psi K^*$ but also their helicity components of decay amplitudes are consistent with current experimental data. It will guarantee that our predicted results on $f_0(980)$ productions of B decays are reliable.

Since the hadronic transition matrix elements of penguin effects in $\bar{B}\to J/\psi M$, $M=K$, K^*, and $f_0(980)$, can be related to tree ones, we describe the effective Hamiltonian for the $b\to c\bar{q}d$ transition as

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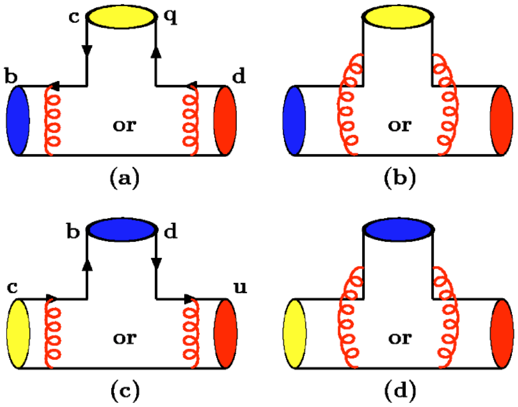

FIG. 1. (a) and (b) illustrate the factorizable and nonfactorizable emission topologies, respectively, while (c) and (d) correspond to the annihilation topologies.

$$H_{\rm eff}=\frac{G_F}{\sqrt{2}}\sum_{q=u,c}V_q[C_1(\mu)\mathcal{O}_1^{(q)}+C_2(\mu)\mathcal{O}_2^{(q)}] \qquad (1)$$

with $\mathcal{O}_1^{(q)}=\bar{d}_\alpha q_\beta \bar{c}_\beta b_\alpha$ and $\mathcal{O}_2^{(q)}=\bar{d}_\alpha q_\alpha \bar{c}_\beta b_\beta$, where $\bar{q}_\alpha q_\beta=\bar{q}_\alpha\gamma_\mu(1-\gamma_5)q_\beta$, $\alpha(\beta)$ are the color indices, $V_q=V_{qd}^* V_{cb}$ are the products of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, and $C_{1,2}(\mu)$ are the Wilson coefficients (WCs) [23]. Conventionally, the effective WCs of $a_2=C_1+C_2/N_c$ and $a_1=C_2+C_1/N_c$ with $N_c=3$ being a color number are more useful. $q=u$ corresponds to $\bar{B}\to D^{(*)0}M$ decays while $q=c$ stands for $\bar{B}\to J/\psi M$ decays. According to the effective operators in Eq. (1), we find that only emission topologies contribute to $\bar{B}\to J/\psi f_0(980)$, however, the decays of $\bar{B}\to D^{(*)0}f_0(980)$ involve both emission and annihilation topologies. To be more clear, the illustrated diagrams are displayed in Fig. 1. From the figure, we could see obviously that only $n\bar{n}$ content has the contributions, and the factorizable emission parts, Fig. 1(a), are only related to the $\bar{B}\to f_0(980)$ form factor. We note that in the color-suppressed processes the nonfactorizable effects, shown as Figs. 1(b) and 1(d), are important and should be considered.

Regarding $f_0(980)$ as $q\bar{q}$ contents in B decays, the immediate question is how to write down the corresponding hadronic structures and the associated wave functions for this ${}^3P_0$ state. What we know is that the spin structures of $f_0(980)$ should satisfy $\langle 0|\bar{q}\gamma_\mu q|f_0(980)\rangle=0$ and $\langle 0|\bar{q}q|f_0(980)\rangle=m_{f_0}\tilde{f}$ in which $m_{f_0}(\tilde{f}\approx 0.18)$ [11] is the mass (decay constant) of $f_0(980)$. In order to satisfy these local current matrix elements, the light-cone distribution amplitude for $f_0(980)$ should be given by

$$\langle 0|\bar{q}(0)_j q(z)_l|f_0\rangle=\frac{1}{\sqrt{2N_c}}\int_0^1 dx\, e^{-ixP\cdot z}\times\{[\not{p}]_{lj}\Phi_{f_0}(x)+m_f[\mathbf{1}]_{lj}\Phi_{f_0}^p(x)\}, \qquad (2)$$

where $\Phi_{f_0}^{(p)}(x)$ belong to twist-2(3) wave functions. The charge parity indicates that $\Phi_{f_0}(x)=-\Phi_{f_0}(1-x)$ and $\Phi^p_{f_0}(x)=\Phi^p_{f_0}(1-x)$ [24] so that their normalizations are $\int_0^1 dx\Phi_{f_0}(x)=0$ and $\int_0^1 dx\Phi^p_{f_0}(x)=\tilde{f}/2\sqrt{2N_c}$. As usual, we adopt a good approximation that the light-cone wave functions are expanded in Gegenbauer polynomials. Therefore, we choose

$$\Phi^p_{f_0}(x)=\frac{\tilde{f}}{2\sqrt{2N_c}}\{3(1-2x)^2+G_1^p(1-2x)^2\times[C_2^{3/2}(1-2x)-3]+G_2^p C_4^{1/2}(1-2x)\},$$

$$\Phi_{f_0}(x)=\frac{\tilde{f}}{2\sqrt{2N_c}}G[6x(1-x)C_1^{3/2}(1-2x)], \qquad (3)$$

where C_n^λ are the Gegenbauer polynomials and the values of coefficients $\{G\}$ have not been determined yet from the first principle QCD approach.

It has been shown that by the employ of hierarchy $M_B\gg M_{D^{(*)}}\gg\bar{\Lambda}$, the $D^{(*)}$ meson distribution amplitudes could be described by [25]

$$\langle 0|\bar{d}(0)_j c(z)_l|D\rangle=\frac{1}{\sqrt{2N_c}}\int_0^1 dx\, e^{-ixP\cdot z}\{[\not{p}+M_D]_{lj}\gamma_5\Phi_D(x)\},$$

$$\langle 0|\bar{d}(0)_j c(z)_l|D^*\rangle=\frac{1}{\sqrt{2N_c}}\int_0^1 dx\, e^{-ixP\cdot z}\{[\not{p}+M_{D^*}]_{lj}\not{\varepsilon}\Phi_{D^*}(x)\}, \qquad (4)$$

where ε_μ is the polarization vector of D^*, the normalizations of wave functions are taken as $\int_0^1 dx\Phi_{D^{(*)}}(x)=f_{D^{(*)}}/2\sqrt{2N_c}$, and $f_{D^{(*)}}$ are the corresponding decay constants. Although the decay constants and wave functions of the D^{*0} meson for longitudinal and transverse polarizations are different generally, for simplicity, in our estimations we assume that they are the same. Since the hadronic structure of B was studied before, the explicit description can be found in Ref. [27]. In order to fit the measured BR of $\bar{B}\to D^0\pi^0$, the involved $D^{(*)}$ wave functions are modeled simply as [25]

$$\Phi_{D^{(*)}}(x)=\frac{3}{\sqrt{2N_c}}f_{D^{(*)}}x(1-x)[1+0.7(1-2x)]. \qquad (5)$$

With the same guidance, we also apply the concept to the J/ψ case. As a detailed discussion, one can refer to Ref. [26].

As mentioned before, due to a large energy transfer in heavy B meson decays, we can utilize the factorization theorem, in which decay amplitudes can be calculated by the convolution of hard parts and wave functions [18,19] to describe the hadronic effects. Although vector D^{*0} and J/ψ

mesons carry the spin degrees of freedom, in the $\bar{B}\to D^{*0}(J/\psi)f_0(980)$ decays only longitudinal polarization is involved. Expectably, the results should be similar to the $D^0 f_0(980)$ mode. Hence, we only present the representative formulas for $\bar{B}\to D^0 f_0(980)$ at the amplitude level but give the predicted BRs for all considered processes. From Fig. 1 and the effective interactions of Eq. (1), the decay amplitude for $\bar{B}\to D^0 f_0(980)$ is written by

$$A_{nn}^{-}=\frac{\sin\phi_s}{\sqrt{2}}V_u[f_D\mathcal{F}_e+\mathcal{M}_e+f_B\mathcal{F}_a+\mathcal{M}_a]$$

where $\mathcal{F}_e(\mathcal{M}_e)$ and $\mathcal{F}_a(\mathcal{M}_a)$ are the factorized (nonfactorized) emission and annihilation hard amplitudes, respectively. According to Eqs. (2) and (4), the typical hard functions are expressed as

$$\mathcal{F}_e=\zeta\int_0^1 dx_1\,dx_3\int_0^\infty b_1\,db_1\,b_3\,db_3\,\Phi_B(x_1,b_1)\times\{[(1+x_3)\Phi_{f_0}(x_3)+r_f(1-2x_3)\Phi_{f_0}^p(x_3)]\times\mathcal{E}_e(t_e^1)+2r_f\Phi_{f_0}^p(x_3)\mathcal{E}_e(t_e^2)\},\quad(6)$$

$$\mathcal{M}_e=2\zeta\int_0^1 d[x]\int_0^\infty b_1\,db_1\,b_3\,db_3\,\Phi_B(x_1,b_1)\Phi_D(x_2)\times\{[-(x_2+x_3)\Phi_{f_0}(x_3)+r_fx_3\Phi_{f_0}^p(x_3)]\mathcal{E}_d^1(t_d^1)+[(1-x_2)\Phi_{f_0}(x_3)-r_fx_3\Phi_{f_0}^p(x_3)]\mathcal{E}_d^2(t_d^2)\},\quad(7)$$

with

$$\zeta=8\pi C_F M_B^2,$$

$$r_f=m_f/M_B,$$

$$\mathcal{E}_e^i(t_e^i)=\alpha_s(t_e^i)a_2(t_e^i)Su_{B+f_0(980)}(t_e^i)h_e(\{x\},\{b\}),$$

and

$$\mathcal{E}_d^i(t_d^i)=\alpha_s(t_d^i)[C_2(t_d^i)/N_c]$$

$$Su(t_d^i)_{B+D+f_0(980)}h_d(\{x\},\{b\}).$$

$t_{e,d}^{1,2}$, Su, and $h_{e,d}$ denote the hard scales of B decays, Sudakov factors, and hard functions arising from the propagators of gluon and internal valence quarks, respectively. Their explicit expressions can be found in Ref. [27]. With the same procedure, the other hard functions can also be derived.

So far, the still uncertain values are the $\{G\}$ parameters of the $f_0(980)$ wave functions. By the identity of $\langle 0|\bar{q}\gamma_\mu q|V,T\rangle=M_V f_V\varepsilon_\mu(T)$ for the V-meson transverse polarization, we find that except the Dirac matrices γ_μ and the associated polarization vector ε_μ, it is similar to the scalar meson case. Inspired by the similarity, we adopt $\Phi_{f_0}^p(x)$ to be a ρ-meson-like wave function and take $G_1^p\approx1.5$ and $G_2^p\approx1.8$ [28]. As to the value of G, we use the corresponding value in $a_0(980)$ given by the second reference of [24] and get $G\approx1.11$. By the chosen values and using Eq. (6) with excluding WC of a_2, we immediately get the $\bar{B}\to f_0(980)$ form factor to be 0.38. Is it a reasonable value? In order to investigate that the obtained value is proper, we employ the relationship $F^{B\to f_0(980)}\sim(M_{D_s}/M_B)^{1/2}F^{D_s\to f_0(980)}$, which comes from the heavy quark symmetry limit [29], as a test. According to the calculation of Ref. [30], we know $F^{D_s\to f_0(980)}\approx0.6$; and then, we have $F^{B\to f_0(980)}\sim0.36$. Clearly, it is quite close to what we obtain. Hence, with the taken values of parameters, the magnitudes of hard functions are given in Table I. We note that the complex values come from the on-shell internal quark and all of the hard functions are the same in order of magnitude.

TABLE I. Hard functions (in units of 10^{-2}) for $\bar{B}\to D^0 f_0(980)$ decay with $\tilde{f}=0.18$, $f_D=0.2$ GeV, $G=1.11$, $G_1^p=1.5$, and $G_2^p=1.8$.

Amplitude	$\mathcal{F}_e$	$\mathcal{M}_e$	$\mathcal{F}_a$	$\mathcal{M}_a$
$D^0 f_0(980)$	-5.95	$-2.66+i1.56$	$1.83-i3.60$	$0.20+i1.12$

One challenging question is how reliable our results are. In order to investigate this point, besides the $\bar{B}\to D^{(*)0}(J/\psi)f_0(980)$ decays, we also calculate $\bar{B}\to D^0\pi$, $J/\psi(K,K^*)$ and $\bar{B}\to f_0(980)K^+$ processes. All of them are already measured at B factories [31,32]. Due to the calculations and formalisms being similar to $D^0 f_0(980)$, we directly present the predicted BRs in Table II by taking $\phi_s=45°$, $f_{D^*}=0.22$ GeV, $f_{J/\psi}=0.405$ GeV, and the same taken values of Table I. As to the J/ψ wave functions, we model it as $\Phi_{J/\psi}(x)=f_{J/\psi}[30x^2(1-x)^2]/2\sqrt{2N_c}$. The BRs of charged $B^+\to J/\psi M^+$ modes can be obtained from neutral modes by using $\mathrm{Br}(\bar{B}^0\to J/\psi M^0)\tau_{B^+}/\tau_{B^0}$. Hence, from Table II, we clearly see that our predictions are consistent with experimental data.

Moreover, it is worthwhile to mention that in addition to the BR of $\bar{B}\to J/\psi K^*$ decay, the squared helicity amplitudes $|A_0|^2$, $|A_\parallel|^2$, and $|A_\perp|^2$ with the normalization of $|A_0|^2$

TABLE II. BRs (in units of 10^{-4}) with $\phi_s=45°$, $f_{D^*}=0.22$, $f_{J/\psi}=0.405$ GeV, and the same taken values of Table I.

Mode	Belle [31]	BaBar [32]	This work
$D^0 f_0(980)$			2.28
$D^{*0} f_0(980)$			2.46
$J/\psi f_0(980)$			0.10
$K^+ f_0(980)$			
$f_0\to\pi^+\pi^-$	$(9.6^{+2.5+1.5+3.4}_{-2.3-1.5-0.8})\times10^{-2}$		0.02
$D^0\pi^0$	$3.1\pm0.4\pm0.5$	$2.89\pm0.29\pm0.38$	2.60
$J/\psi K^0$	$7.9\pm0.4\pm0.9$	$8.3\pm0.4\pm0.5$	8.3
$J/\psi K^{*0}$	$12.9\pm0.5\pm1.3$	$12.4\pm0.5\pm0.9$	13.37

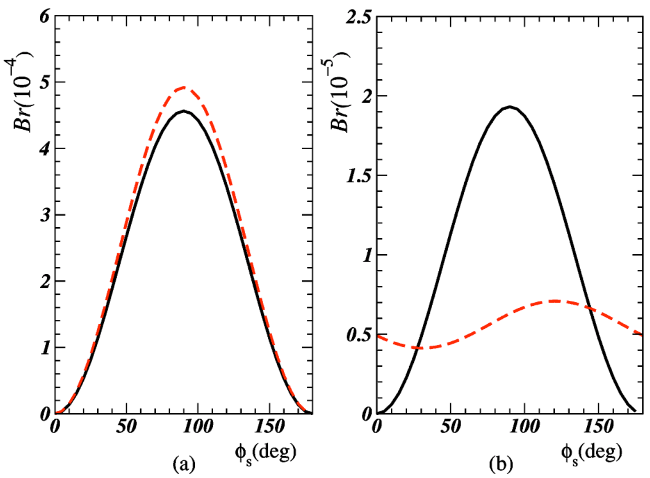

FIG. 2. BRs as a function of angle ϕ_s. (a) The solid (dashed) lines are for $\bar{B}\to D^0(D^{*0})f_0(980)$ decays while (b) they express $\bar{B}\to J/\psi f_0(980)$ and $B^+\to K^+f_0(980)$ decays.

$+|A_\parallel|^2+|A_\perp|^2=1$ [33] are also given as 0.59, 0.24, and 0.17, respectively. They are all comparable with the measured values 0.60 ± 0.05 (0.60 ± 0.04), 0.21 ± 0.08 (0.24 ± 0.04), and 0.19 ± 0.06 (0.16 ± 0.03) of Belle (BaBar) [31,32]. In order to further understand the dependence of the effects of $n\bar{n}$ content, the BRs as a function of mixing angle ϕ_s are shown in Fig. 2. We note that with including the twist-2 wave function for $f_0(980)$, our previous result of $B^+\to K^+f_0(980)$ in the small ϕ_s region [28] becomes insensitive to ϕ_s.

The subsequent question is how to search the events for $\bar{B}\to D^{(*)0}f_0(980)$ and $\bar{B}\to J/\psi f_0(980)$ decays. From Particle Data Group of Ref. [22], we know that $f_0(980)$ mainly decays to $\pi\pi$ and KK and $R=\Gamma(\pi\pi)/[\Gamma(\pi\pi)+\Gamma(KK)]$ ~0.68. Therefore, we suggest that the candidates could be found in $\bar{B}\to D^{(*)0}(J/\psi)\pi\pi(KK)$ three-body decay samples. For an illustration, according to the values of Table II, we can estimate that the BR product of $\mathrm{Br}[\bar{B}\to D^0f_0(980)]\times\mathrm{Br}[f_0(980)\to\pi^+\pi^-]\approx1.0\times10^{-4}$ with $\mathrm{Br}[f_0(980)\to\pi^+\pi^-]=2R/3$. The result is consistent with the measured value of $(8.0\pm0.6\pm1.5)\times10^{-4}$ for $\bar{B}\to D^0\pi^+\pi^-$ decay while that of $\bar{B}\to D^0\rho^0$ is determined to be $(2.9\pm1.0\pm0.4)\times10^{-4}$ [34].

We have investigated the possibility to extract the existence of the $n\bar{n}$ component of $f_0(980)$ in terms of $\bar{B}\to D^{(*)0}f_0(980)$ and $\bar{B}\to J/\psi f_0(980)$ decays. Based on the comparable values between the BRs of $\bar{B}\to D^0\pi^0$ and $\bar{B}\to J/\psi M$ decays and current experimental data, our predictions on the BRs of $\bar{B}\to D^{(*)0}(J/\psi)f_0(980)$ decays are reliable and can be tested at B factories.

The author would like to thank H.N. Li and H.Y. Cheng for their useful discussions. This work was supported in part by the National Science Council of the Republic of China under Grant No. NSC-91-2112-M-001-053.

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