CPC(HEP & NP), 2010, **34**(5): 528–534 Chinese Physics C Vol. 34, No. 5, May, 2010

Study of scalar meson $a_0(980)$ from $B \to a_0(980)\pi$ decays*

ZHANG Zhi-Qing(张志清)[1,2;1)] XIAO Zhen-Jun(肖振军)[2;2)]

[1] Department of Physics, Henan University of Technology, Zhengzhou, Henan 450052, China
[2] Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing, Jiangsu 210097, China

Abstract In this paper, we calculate the branching ratios and the direct CP-violating asymmetries for decays $\overline{B}^0 \to a_0^0(980)\pi^0$, $a_0^+(980)\pi^-$, $a_0^-(980)\pi^+$ and $B^- \to a_0^0(980)\pi^-$, $a_0^-(980)\pi^0$ by employing the perturbative QCD (pQCD) factorization approach at the leading order. We found that (a) the pQCD predictions for the branching ratios are around $(0.4-2.8)\times 10^{-6}$, consistent with currently available experimental upper limits; (b) the CP asymmetries of $\overline{B}^0 \to a_0^0(980)\pi^0$ and $B^- \to a_0^-(980)\pi^0$ decays can be large, about (70–80)% for $\alpha = 100^\circ$.

Key words B meson decay, the pQCD factorization approach, branching ratio, CP asymmetry

PACS 13.25.Hw, 12.38.Bx, 14.40.Nd

1 Introduction

The study about scalar meson is an interesting topic for both theory and experiment. In order to uncover their mysterious structure, intensive studies have been done for the B meson decays involving a scalar meson as one of the two final state mesons. Such decays have been studied by employing various factorization approaches, such as the QCD factorization (QCDF) approach [1], the perturbative QCD (pQCD) approach [2–5], and by using the QCD sum rule [6].

On the experimental side, the scalar meson $f_0(980)$ was observed in the decay mode $B \to f_0(980)K$ by Belle [7], and confirmed by BaBar [8] later. Then many channels involving a scalar in the final state have been measured by Belle [9] and BaBar [10]. The decays $B \to a_0(980)\pi$ have also been studied by BarBar [11], In Ref. [12] the authors argued that if the branching ratio of $B^- \to a_0^-(980)\pi^0$ decay can be measured accurately, one can separate the four- and two-quark assignments, because the predictions of these two assignments have a difference of one order of magnitude. So in the past three years, BarBar has given this channel two measurements [13] and got two almost identical upper limits. For our considered decays, only the experimental upper limits are available now for some of them [14]:

$$\begin{aligned} Br(\overline{B}^0 \to a_0^+(980)\pi^-) &< 3.1\times 10^{-6}, \\ Br(B^- \to a_0^-(980)\pi^0) &< 1.4\times 10^{-6}, \\ Br(B^- \to a_0^0(980)\pi^-) &< 5.8\times 10^{-6}. \end{aligned} \quad (1)$$

In this paper, we will study the branching ratios and CP asymmetries of $\overline{B}^0 \to a_0^0(980)\pi^0$, $a_0^\pm(980)\pi^\mp$ and $B^- \to a_0^-(980)\pi^0$, $a_0^0(980)\pi^-$ by employing the pQCD factorization approach. In the following, we use a_0 to denote $a_0(980)$ in some places for convenience. The paper is organized as follows. In Sec. 2, the status of the study on the physical properties of a_0, the relevant decay constants and light-cone distribution amplitudes are discussed. In Sec. 3, we then study these decay channels using the pQCD approach. The numerical results and the discussions are given in Section 4. The conclusions are presented in the final section.

2 Physical properties of the final particles

Many scalar mesons below 2 GeV have been found in experiments. We can not accommodate these scalar mesons into one nonet, but need at least two nonets below and above 1 GeV [15]. Among them, the scalar mesons below 1 GeV, including $f_0(600)(\sigma)$,

Received 22 July 2009, Revised 10 December 2009
* Supported by National Natural Science Foundation of China (10575052, 10735080)
1) E-mail: zhangzhiqing@zzu.edu.cn
2) E-mail: xiaozhenjun@njnu.edu.cn

$f_0(980)$, $K_0^*(800)(\kappa)$ and $a_0(980)$, are usually viewed to form a $SU(3)$ nonet; while scalar mseons above 1 GeV, including $f_0(1370)$, $f_0(1500)$/ $f_0(1700)$, $K^*(1430)$ and $a_0(1450)$ form another $SU(3)$ nonet. There are several different scenarios to describe these mesons in the quark model [16–19]. For example, the $a_0(980)$ meson has been suggested as a $\bar{q}q$ lowest lying state [16] (called scenario Ⅰ) or a four-quark bound state [17] (called scenario Ⅱ). In Scenario Ⅰ, the former $SU(3)$ nonet mesons are treated as the $\bar{q}q$ ground stats, while the latter nonet ones are the first excited states; in Scenario Ⅱ, the former nonet mesons are viewed as four-quark bound states, while the latter nonet ones are $\bar{q}q$ ground states. Some people also consider that it is not made of one simple component but might have a more complex nature such as having a $K\bar{K}$ component [18, 19], even the superpositions of the two- and four- quark states. In order to make quantitative predictions, we identify $a_0(980)$ as the two-quark state in the calculation.

In the 2-quark model, the decay constants for scalar meson a_0 are defined by:

$$\langle a_0(p)|\bar{q}_2\gamma_\mu q_1|0\rangle = f_{a_0}p_\mu,\ \langle a_0(p)|\bar{q}_2 q_1|0\rangle = m_{a_0}\bar{f}_{a_0}. \quad (2)$$

Since the neutral scalar meson a_0 cannot be produced via the vector current (restricted by the charge conjugation invariance or the G parity conservation), the vector decay constant $f_{a_0}=0$. As to the charged scalar mesons a_0^-, from the equation of motion:

$$\mu_{a_0^-}f_{a_0^-}=\bar{f}_{a_0^-}, \quad \text{with} \quad \mu_{a_0^-}=\frac{m_{a_0^-}}{m_d(\mu)-m_u(\mu)}, \quad (3)$$

its vector decay constant is proportional to the mass difference between the constituent u and d quarks. It is easy to see the vector decay constant is very small, and will equal zero in the $SU(3)$ limit. So we only need to consider the scalar decay constant $\bar{f}_{a_0}$, which is scale dependent. Fixing the scale at 1 GeV, the value is $\bar{f}_{a_0}=(365\pm20)$ MeV, which is calculated in QCD sum rules [1].

The light-cone distribution amplitudes (LCDAs) for the scalar meson a_0 can be written as:

$$\langle a_0(p)|\bar{q}_1(z)_l q_2(0)_j|0\rangle = \frac{1}{\sqrt{6}}\int_0^1 dx\, e^{ix\,p\cdot z}\Big\{\not p\,\Phi_{a_0}(x) + m_{a_0}\Phi^S_{a_0}(x)+m_{a_0}(\not n_+\not n_- -1)\Phi^T_{a_0}(x)\Big\}_{jl}, \quad (4)$$

where n_+ and n_- are the light-like vectors: $n_+=(1,0,0_T)$, $n_-=(0,1,0_T)$, and n_+ is parallel with the moving direction of the scalar meson a_0. The normalization can be related to the decay constants:

$$\int_0^1 dx\Phi_{a_0}(x)=\int_0^1 dx\Phi^T_{a_0}(x)=0,$$
$$\int_0^1 dx\Phi^S_{a_0}(x)=\frac{\bar{f}_{a_0}}{2\sqrt{2N_c}}. \quad (5)$$

The twist-2 LCDA can be expanded in the Gegenbauer polynomials:

$$\Phi_{a_0}(x,\mu) = \frac{1}{2\sqrt{2N_c}}\bar{f}_{a_0}(\mu)6x(1-x)\times \sum_{m=1}^{\infty}B_m(\mu)C_m^{3/2}(2x-1), \quad (6)$$

the values for Gegenbauer moments B_1, B_3 have been calculated in Ref. [1] as:

$$B_1=-0.93\pm0.10, \quad B_3=0.14\pm0.08. \quad (7)$$

These values are taken at $\mu=1$ GeV and the even Gegenbauer moments vanish.

As for the twist-3 distribution amplitudes $\Phi^S_{a_0}$ and $\Phi^T_{a_0}$, they have not been studied in the literature, so we adopt the asymptotic form [5]:

$$\Phi^S_{a_0} = \frac{1}{2\sqrt{2N_c}}\bar{f}_{a_0},$$
$$\Phi^T_{a_0} = \frac{1}{2\sqrt{2N_c}}\bar{f}_{a_0}(1-2x). \quad (8)$$

3 The perturbative QCD calculation

In the pQCD approach, the decay amplitude of $B\to a_0\pi$ decays can be conceptually written as the convolution,

$$\mathcal{A}(B\to\pi a_0)\sim\int d^4k_1 d^4k_2 d^4k_3\times \mathrm{Tr}\left[C(t)\Phi_B(k_1)\Phi_\pi(k_2)\Phi_{a_0}(k_3)H(k_1,k_2,k_3,t)\right], \quad (9)$$

where k_i's are the momenta of light quarks included in each mesons, and Tr denotes the trace over Dirac and color indices. $C(t)$ is the Wilson coefficient, $H(k_1,k_2,k_3,t)$ is the hard kernel which describes the four quark operator and the spectator quark connected by a hard gluon, and can be perturbatively calculated. The functions Φ_B, Φ_π and Φ_{a_0} are the wave functions of the B, π and a_0 meson, respectively.

Since the b quark is rather heavy we consider the B meson at rest for simplicity. It is convenient to use light-cone coordinate $(p^+,p^-,\boldsymbol{p}_T)$ to describe the meson's momenta: $p^\pm=(p^0\pm p^3)/\sqrt{2}$, and $\boldsymbol{p}_T=(p^1,p^2)$. Using these coordinates the B meson and the two final state meson momenta can be written as

$$\begin{aligned} P_{\rm B} &= \frac{M_{\rm B}}{\sqrt{2}}(1,1,\mathbf{0}_{\rm T}), \\ P_2 &= \frac{M_{\rm B}}{\sqrt{2}}(1,0,\mathbf{0}_{\rm T}), \\ P_3 &= \frac{M_{\rm B}}{\sqrt{2}}(0,1,\mathbf{0}_{\rm T}), \end{aligned} \tag{10}$$

respectively. The light meson masses m_π and $m(\rm a_0)$ have been neglected. Putting the anti- quark momenta in B, π and $\rm a_0$ mesons as k_1, k_2, and k_3, respectively, we can choose

$$\begin{aligned} k_1 &= (x_1P_1^+,0,\boldsymbol{k}_{1\rm T}), \\ k_2 &= (x_2P_2^+,0,\boldsymbol{k}_{2\rm T}), \\ k_3 &= (0,x_3P_3^-,\boldsymbol{k}_{3\rm T}). \end{aligned} \tag{11}$$

For these considered decay channels, the integration over k_1^-, k_2^-, and k_3^+ in Eq. (9) will lead to

$$\begin{aligned} \mathcal{A}(\mathrm{B}\to\pi \mathrm{a}_0) \sim & \int \mathrm{d}x_1\mathrm{d}x_2\mathrm{d}x_3 b_1\mathrm{d}b_1 b_2\mathrm{d}b_2 b_3\mathrm{d}b_3 \times \\ & \mathrm{Tr}\big[C(t)\Phi_{\rm B}(x_1,b_1)\Phi_\pi(x_2,b_2)\times \\ & \Phi_{\rm a_0}(x_3,b_3)H(x_i,b_i,t)S_t(x_i)\,\mathrm{e}^{-S(t)}\big], \end{aligned} \tag{12}$$

where b_i is the conjugate space coordinate of $k_{i\rm T}$, and t is the largest energy scale in function $H(x_i,b_i,t)$. In order to smear the end-point singularity on x_i, the jet function $S_{\rm t}(x)$ [20], which comes from the resummation of the double logarithms $\ln^2 x_i$, is used

$$S_{\rm t}(x) = \frac{2^{1+2c}\Gamma(3/2+c)}{\sqrt{\pi}\Gamma(1+c)}[x(1-x)]^c\ , \tag{13}$$

where the parameter $c=0.4$. The last term $\mathrm{e}^{-S(t)}$ in Eq. (12) is the Sudakov form factor which suppresses the soft dynamics effectively [21].

For the considered decays, the related weak effective Hamiltonian $\mathcal{H}_{\rm eff}$ can be written as [22]

$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}}\sum_{\rm q=u,c} V_{\rm qb}V_{\rm qd}^*\Bigg[\Big(C_1(\mu)O_1^q(\mu)+C_2(\mu)O_2^q(\mu)\Big)\times \sum_{i=3}^{10} C_i(\mu)\,O_i(\mu)\Bigg], \tag{14}$$

with $G_{\rm F} = 1.16639\times10^{-5}$ GeV^{-2} is the Fermi constant, V_{ij} are the CKM matrix elements, $C_i(\mu)$ and $O_i(\mu)$ are the Wilson coefficients and the corresponding 4-quark operators.

In the following, we take the $\overline{\rm B}^0 \to \pi^0 \rm a_0^0$ decay channel as an example. There are 8 type diagrams contributing to this decay, as illustrated in Fig. 1. For the factorizable emission diagrams (a) and (b), operators $O_{1-4,9,10}$ are $(V-A)(V-A)$ currents, and the operators O_{5-8} have a structure of $(V-A)(V+A)$, the sum of the amplitudes are written as $F_{\rm e\pi}$ and $F_{\rm e\pi}^{P1}$. In some other cases, we need to do Fierz transformation for the $(V-A)(V+A)$ operators and get $(S-P)(S+P)$ ones which hold the right flavor and color structure for factorization to work. The contribution from the operator $(S-P)(S+P)$ type is written as $F_{\rm e\pi}^{P2}$. Similarly, for the factorizable annihilation diagrams (g) and (h), the contributions from $(V-A)(V-A)$, $(V-A)(V+A)$, $(S-P)(S+P)$ currents are $F_{\rm a\pi}$, $F_{\rm a\pi}^{P1}$ and $F_{\rm a\pi}^{P2}$. For the nonfactorizable spectator diagrams (c, d) and the nonfactorizable annihilation diagrams (e, f), these three kinds of contributions can be written as $M_{\rm e\pi}, M_{\rm e\pi}^{P1}$, $M_{\rm e\pi}^{P2}$ and $M_{\rm a\pi}$, $M_{\rm a\pi}^{P1}$, $M_{\rm a\pi}^{P2}$, respectively. Since these amplitudes are similar to those of $\rm B\to f_0(980)K(\pi,\eta^{(\prime)})$ [3, 4] or $\rm B\to a_0(980)K$ [5], we just need to replace some corresponding wave functions and parameters.

Combining the contributions from different diagrams, the total decay amplitudes for those considered decays can be written as:

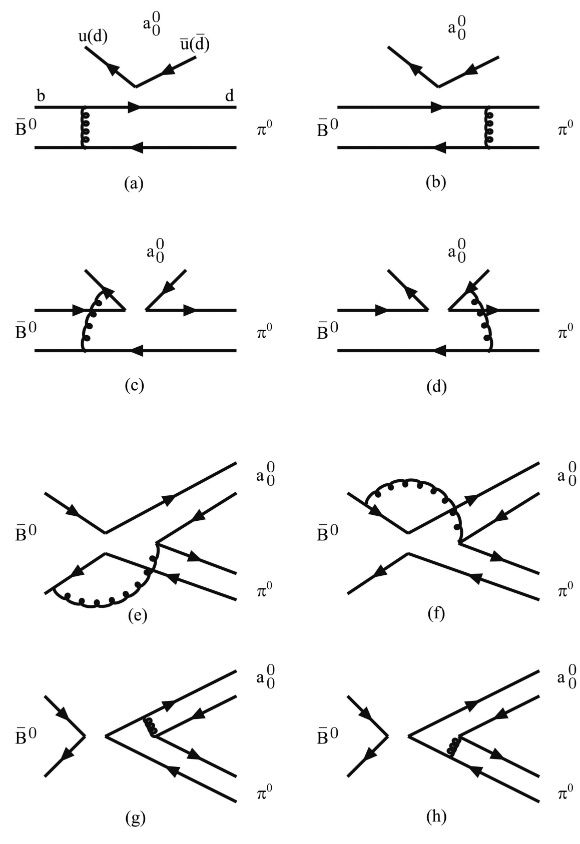

Fig. 1. Typical Feynman diagrams contributing to the decay $\overline{\rm B}^0\to\pi^0\rm a_0^0$.

$$\begin{aligned}2\mathcal{M}(\overline{B}^0\to a_0^0\pi^0) =\; & \xi_u[(-M_{e\pi}+M_{a\pi}+M_{ea_0}+M_{aa_0})C_2+(F_{a\pi}+F_{ea_0}+F_{aa_0})a_2]- \\ & \xi_t\left\{\left(M_{e\pi}^{P1}+M_{a\pi}^{P1}+M_{ea_0}^{P1}+M_{aa_0}^{P1}\right)\left(C_5-\frac{1}{2}C_7\right)+\right. \\ & (M_{e\pi}+M_{a\pi}+M_{ea_0}+M_{aa_0})\left(C_3+2C_4-\frac{1}{2}C_9+\frac{1}{2}C_{10}\right)+ \\ & \left(M_{e\pi}^{P2}+M_{a\pi}^{P2}+M_{ea_0}^{P2}+M_{aa_0}^{P2}\right)\left(2C_6+\frac{1}{2}C_8\right)+ \\ & (F_{a\pi}+F_{ea_0}+F_{aa_0})\left(2a_3+a_4-2a_5-\frac{1}{2}a_7+\frac{1}{2}a_9-\frac{1}{2}a_{10}\right)+ \\ & \left.\left(F_{e\pi}^{P2}+F_{a\pi}^{P2}+F_{ea_0}^{P2}+F_{aa_0}^{P2}\right)\left(a_6-\frac{1}{2}a_8\right)\right\}, \end{aligned} \tag{15}$$

$$\begin{aligned}\mathcal{M}(\overline{B}^0\to a_0^-\pi^+) =\; & \xi_u[F_{aa_0}a_2+M_{e\pi}C_1+M_{aa_0}C_2]-\xi_t\left\{M_{a\pi}^{P1}\left(C_5-\frac{1}{2}C_7\right)+\right. \\ & M_{e\pi}^{P1}(C_5+C_7)+M_{a\pi}\left(C_3+C_4-\frac{1}{2}C_9-\frac{1}{2}C_{10}\right)+M_{aa_0}(C_4+C_{10})+ \\ & M_{e\pi}(C_3+C_9)+M_{a\pi}^{P2}\left(C_6-\frac{1}{2}C_8\right)+M_{aa_0}^{P2}(C_6+C_8)+ \\ & F_{a\pi}\left(a_3+a_4-a_5+\frac{1}{2}a_7-\frac{1}{2}a_9-\frac{1}{2}a_{10}\right)+ \\ & \left.F_{aa_0}(a_3+a_9-a_5-a_7)+F_{e\pi}^{P2}(a_6+a_8)+F_{a\pi}^{P2}\left(a_6-\frac{1}{2}a_8\right)\right\}, \end{aligned} \tag{16}$$

$$\begin{aligned}\mathcal{M}(\overline{B}^0\to a_0^+\pi^-) =\; & \xi_u[F_{ea_0}a_1+F_{a\pi}a_2+M_{ea_0}C_1+M_{a\pi}C_2]-\xi_t\left\{M_{aa_0}^{P1}\left(C_5-\frac{1}{2}C_7\right)+\right. \\ & M_{ea_0}^{P1}(C_5+C_7)+M_{aa_0}\left(C_3+C_4-\frac{1}{2}C_9-\frac{1}{2}C_{10}\right)+M_{a\pi}(C_4+C_{10})+ \\ & M_{ea_0}(C_3+C_9)+M_{aa_0}^{P2}\left(C_6-\frac{1}{2}C_8\right)+M_{a\pi}^{P2}(C_6+C_8)+ \\ & F_{aa_0}\left(a_3+a_4-a_5+\frac{1}{2}a_7-\frac{1}{2}a_9-\frac{1}{2}a_{10}\right)+F_{ea_0}(a_4+a_{10})+ \\ & \left.F_{a\pi}(a_3+a_9-a_5-a_7)+F_{ea_0}^{P2}(a_6+a_8)+F_{aa_0}^{P2}\left(a_6-\frac{1}{2}a_8\right)\right\}, \end{aligned} \tag{17}$$

$$\begin{aligned}\sqrt{2}\mathcal{M}(B^-\to a_0^0\pi^-) =\; & \xi_u[M_{e\pi}C_2+(-M_{a\pi}+M_{ea_0}+M_{aa_0})C_1+(-F_{a\pi}+F_{ea_0}+F_{aa_0})a_1]- \\ & \xi_t\left\{-M_{e\pi}^{P1}\left(C_5-\frac{1}{2}C_7\right)+\left(-M_{a\pi}^{P1}+M_{ea_0}^{P1}+M_{aa_0}^{P1}\right)(C_5+C_7)+\right. \\ & M_{e\pi}\left(-C_3+\frac{1}{2}C_9+\frac{3}{2}C_{10}\right)+(-M_{a\pi}+M_{ea_0}+M_{aa_0})(C_3+C_9)+ \\ & \frac{3}{2}C_8M_{e\pi}^{P2}+(-F_{a\pi}+F_{ea_0}+F_{aa_0})(a_4+a_{10})-F_{e\pi}^{P2}\left(a_6-\frac{1}{2}a_8\right)+ \\ & \left.\left(-F_{a\pi}^{P2}+F_{ea_0}^{P2}+F_{aa_0}^{P2}\right)(a_6+a_8)\right\}, \end{aligned} \tag{18}$$

$$\begin{aligned}\sqrt{2}\mathcal{M}(\mathrm{B}^-\to \mathrm{a}_0^-\pi^0) =\ & \xi_\mathrm{u}\left[M_{\mathrm{ea}_0}C_2+(-M_{\mathrm{aa}_0}+M_{\mathrm{e}\pi}+M_{\mathrm{a}\pi})C_1+F_{\mathrm{ea}_0}a_2+(-F_{\mathrm{aa}_0}+F_{\mathrm{e}\pi}+F_{\mathrm{a}\pi})a_1\right]- \\ & \xi_\mathrm{t}\left\{-M^{P1}_{\mathrm{ea}_0}\left(C_5-\frac{1}{2}C_7\right)+\left(-M^{P1}_{\mathrm{aa}_0}+M^{P1}_{\mathrm{e}\pi}+M^{P1}_{\mathrm{a}\pi}\right)(C_5+C_7)+\right. \\ & M_{\mathrm{ea}_0}\left(-C_3+\frac{1}{2}C_9+\frac{3}{2}C_{10}\right)+(-M_{\mathrm{aa}_0}+M_{\mathrm{e}\pi}+M_{\mathrm{a}\pi})(C_3+C_9)+ \\ & \frac{3}{2}C_8M^{P2}_{\mathrm{ea}_0}+(-F_{\mathrm{aa}_0}+F_{\mathrm{e}\pi}+F_{\mathrm{a}\pi})(a_4+a_{10})-F^{P2}_{\mathrm{ea}_0}\left(a_6-\frac{1}{2}a_8\right)+ \\ & \left.F_{\mathrm{ea}_0}\left(-a_4-\frac{3}{2}a_7+\frac{3}{2}a_9+\frac{1}{2}a_{10}\right)+\left(-F^{P2}_{\mathrm{aa}_0}+F^{P2}_{\mathrm{ea}_0}+F^{P2}_{\mathrm{a}\pi}\right)(a_6+a_8)\right\}, \end{aligned} \quad (19)$$

where $\xi_\mathrm{u}=V_\mathrm{ub}V^*_\mathrm{ud}$, $\xi_\mathrm{t}=V_\mathrm{tb}V^*_\mathrm{td}$, and a_i are the combinations of the Wilson coefficients defined as usual in Ref. [23].

4 Numerical results and discussions

In the numerical calculation, we will use the input parameters as listed in Table 1.

In the B-rest frame, the decay rates of $\mathrm{B}\to\mathrm{a}_0(980)\pi$ can be written as:

$$\Gamma=\frac{G_\mathrm{F}^2}{32\pi m_\mathrm{B}}|\mathcal{M}|^2(1-r^2_{\mathrm{a}_0}), \quad (20)$$

where $r_{\mathrm{a}_0}=m_{\mathrm{a}_0}/m_\mathrm{B}$ and $\mathcal{M}$ is the total decay amplitude of $\mathrm{B}\to\mathrm{a}_0(980)\pi$ as given in the last section.

Using the wave functions as specified in previous section and the input parameters listed in Table 1, it is straightforward to calculate the CP-averaged branching ratios for the considered decays, which are listed in Table 2. In this table, we have included the theoretical errors arising from the uncertainties in the scalar meson decay constant $\bar{f}_{\mathrm{a}_0}$ and the Gengebauaer moments B_1 and B_3 for twist-2 LCDAs of $\mathrm{a}_0(980)$. In Fig. 2, we plot the branching ratios of $\overline{\mathrm{B}}^0\to\mathrm{a}_0^0\pi^0$, $\mathrm{a}_0^-\pi^+$, $\mathrm{a}_0^+\pi^-$ and $\mathrm{B}^-\to\mathrm{a}_0^0\pi^-$, $\mathrm{a}_0^-\pi^0$ as a function of the CKM angle α:

$$\alpha=\arg\left[-\frac{V_\mathrm{td}V^*_\mathrm{tb}}{V_\mathrm{ud}V^*_\mathrm{ub}}\right].$$

From the numerical results, one can see that:

1) Because of the small $\mathrm{u\bar{u}}$ and $\mathrm{d\bar{d}}$ component in the $f_0(980)$, the branching ratio of $\overline{\mathrm{B}}^0\to\mathrm{a}_0^0\pi^0$ is about one order larger than that of $\overline{\mathrm{B}}^0\to\mathrm{f}_0(980)\pi^0$ ($Br(\overline{\mathrm{B}}^0\to\mathrm{f}_0(980)\pi^0)\sim 4.7\times10^{-8}$ [4]), but much smaller than the branching ratio $Br(\overline{\mathrm{B}}^0\to\pi^0\pi^0)=(1.62\pm0.31)\times10^{-6}$.

2) In order to compare with the experimental measurements [11], we also define the branching ratio $Br(\overline{\mathrm{B}}^0\to\mathrm{a}_0^-\pi^++\mathrm{a}_0^+\pi^-)$ as the direct sum of $Br(\overline{\mathrm{B}}^0\to\mathrm{a}_0^-\pi^+)$ and $Br(\overline{\mathrm{B}}^0\to\mathrm{a}_0^+\pi^-)$, and show it in Table 2.

Table 1. Input parameters used in the numerical calculation.

masses	$m_{\mathrm{a}_0}=0.9847$ GeV,	$m_0^\pi=1.3$ GeV,
	$M_\mathrm{B}=5.28$ GeV,	$m_\pi=0.14$ GeV,
decay constants	$f_\mathrm{B}=0.19$ GeV,	$f_\pi=0.13$ GeV,
lifetimes	$\tau_{\mathrm{B}^\pm}=1.671\times10^{-12}$ s,	$\tau_{\mathrm{B}^0}=1.530\times10^{-12}$ s,
CKM	$V_\mathrm{tb}=0.9997$,	$V_\mathrm{td}=0.0081\mathrm{e}^{-\mathrm{i}21.6^\circ}$,
	$V_\mathrm{ud}=0.974$,	$V_\mathrm{ub}=0.00393\mathrm{e}^{-\mathrm{i}60^\circ}$.

Table 2. Branching ratios (in unit of 10^{-6}) for the decays $\overline{\mathrm{B}}^0\to\mathrm{a}_0^0\pi^0,\mathrm{a}_0^\pm\pi^\mp$ and $\mathrm{B}^-\to\mathrm{a}_0^-\pi^0,\mathrm{a}_0^0\pi^-$ by assuming $\alpha=100^\circ$. The first theoretical error is from the the scalar meson decay constant, the second and the third one are Gengebauer moments B_1 and B_3 for twist-2 LCDAs of a(980).

channel	this work	data	QCDF [1]
$\overline{\mathrm{B}}^0\to\mathrm{a}_0^0\pi^0$	$0.51^{+0.08+0.09+0.00}_{-0.07-0.09-0.00}$	–	0.2
$\overline{\mathrm{B}}^0\to\mathrm{a}_0^+\pi^-$	$0.86^{+0.10+0.14+0.01}_{-0.09-0.14-0.00}$	–	7.6
$\overline{\mathrm{B}}^0\to\mathrm{a}_0^-\pi^+$	$0.51^{+0.05+0.09+0.07}_{-0.06-0.09-0.06}$	–	0.6
$\overline{\mathrm{B}}^0\to\mathrm{a}_0^+\pi^-+\mathrm{a}_0^-\pi^+$	$1.37^{+0.11+0.17+0.07}_{-0.12-0.17-0.06}$	<3.1	–
$\mathrm{B}^-\to\mathrm{a}_0^-\pi^0$	$0.41^{+0.00+0.00+0.00}_{-0.13-0.14-0.12}$	<1.4	0.2
$\mathrm{B}^-\to\mathrm{a}_0^0\pi^-$	$2.8^{+0.00+0.00+0.00}_{-0.79-0.85-0.58}$	<5.8	3.4

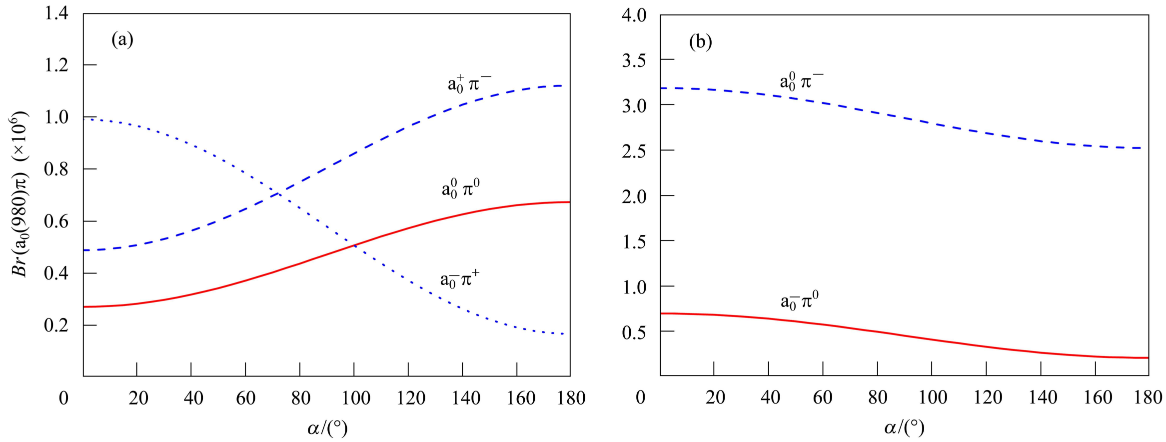

Fig. 2. Branching ratios (in units of 10^{-6}) of (a) $\overline{B}^0 \to a_0^0\pi^0$ (solid curve), $a_0^-\pi^+$ (dotted curve), $a_0^+\pi^-$ (dashed curve) and (b) $B^- \to a_0^-\pi^0$ (solid curve), $B^- \to a_0^0\pi^-$ (dashed curve) decays as a function of the CKM angle α.

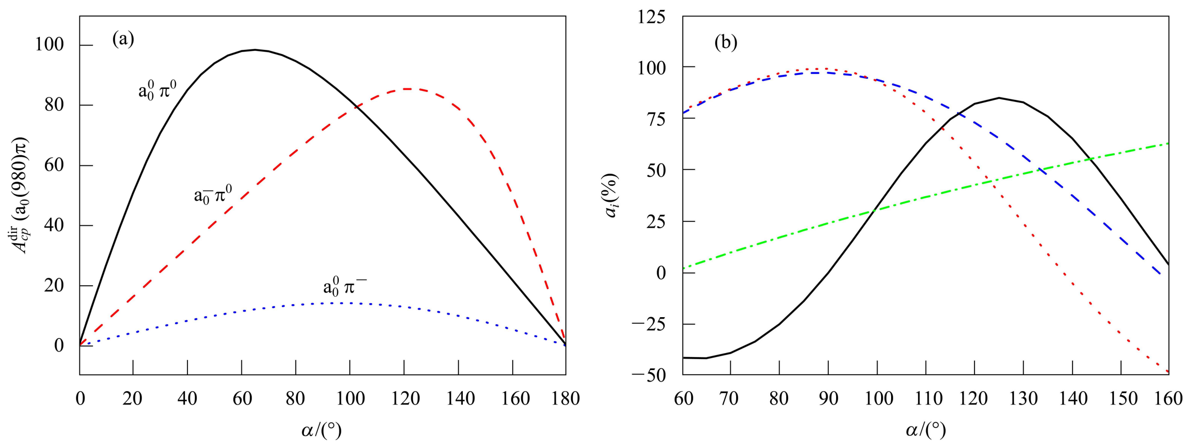

Fig. 3. The direct CP asymmetries (a) of the decays $\overline{B}^0 \to a_0^0\pi^0$ (solid curve), $B^- \to a_0^-\pi^0$ (dashed curve), $B^- \to a_0^0\pi^-$ (dotted cureve) and the CP asymmetry parameters (b) of the decay $B^0/\overline{B}^0 \to a_0^+\pi^- + a_0^-\pi^+$: $a_{\epsilon'}$ (dash-dotted curve), $a_{\overline{\epsilon}'}$ (dotted cureve), $a_{\epsilon+\epsilon'}$ (dashed cureve) and $a_{\epsilon+\overline{\epsilon}'}$ (solid curve) as functions of the CKM angle α.

3) The pQCD predictions for branching ratios are all consistent with currently available experimental upper limits. The 2-quark model supposition of a$_0$(980) can not be ruled out by the current experimental data.

Now we turn to the evaluations of the CP-violating asymmetries of $B^- \to a_0^-\pi^0, a_0^0\pi^-$ and $\overline{B} \to a_0^0\pi^0, a_0^\pm\pi^\mp$ decays in the pQCD approach. For the charged decay channels, the direct CP-violating asymmetry can be defined as $\mathcal{A}_{CP}^{\rm dir} = (|\overline{\mathcal{A}}|^2 - |\mathcal{A}|^2)/(|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2)$. For the neutral decays $\overline{B}^0 \to a_0^0\pi^0$, there are both direct CP asymmetry $\mathcal{A}_{CP}^{\rm dir}$ and mixing-induced CP asymmetry $\mathcal{A}_{CP}^{\rm mix}$:

$$\mathcal{A}_{CP}^{\rm dir}(B_d \to f) = \frac{|\lambda|^2 - 1}{1 + |\lambda|^2},$$

$$\mathcal{A}_{CP}^{\rm mix}(B_d \to f) = \frac{2{\rm Im}\lambda}{1 + |\lambda|^2}, \quad (21)$$

where

$$\lambda = \eta_{CP} e^{-2i\beta} \frac{\mathcal{A}(\overline{B}_d \to f)}{\mathcal{A}(B_d \to f)}$$

with $\eta_{CP} = \pm 1$ the CP eigenvalue of the final state f.

As to the decays $\overline{B} \to a_0^\pm\pi^\mp$, since both B^0 and $\overline{B}^0$ can decay into the final state $a_0^+\pi^-$ and $a_0^-\pi^+$, the four time-dependent decay widths for $B^0(t) \to a_0^+\pi^-$, $\overline{B}^0(t) \to a_0^-\pi^+$, $B^0(t) \to a_0^-\pi^+$ and $\overline{B}^0(t) \to a_0^+\pi^-$ can be expressed by four basic matrix elements:

$$g = \langle a_0^+\pi^-|H_{\rm eff}|B^0\rangle, \quad h = \langle a_0^+\pi^-|H_{\rm eff}|\overline{B}^0\rangle,$$

$$\overline{g} = \langle a_0^-\pi^+|H_{\rm eff}|\overline{B}^0\rangle, \quad \overline{h} = \langle a_0^-\pi^+|H_{\rm eff}|B^0\rangle. \quad (22)$$

Following the notation of Refs. [22, 23], the four CP violating parameters are given by the following formulae:

$$a_{\epsilon'} = \frac{|g|^2-|h|^2}{|g|^2+|h|^2}, \quad a_{\epsilon+\epsilon'} = \frac{-2\mathrm{Im}\left(\frac{q}{p}\frac{h}{g}\right)}{1+|h/g|^2},$$

$$a_{\bar{\epsilon}'} = \frac{|\bar{h}|^2-|\bar{g}|^2}{|\bar{h}|^2+|\bar{g}|^2}, \quad a_{\epsilon+\bar{\epsilon}'} = \frac{-2\mathrm{Im}\left(\frac{q}{p}\frac{\bar{g}}{\bar{h}}\right)}{1+|\bar{g}/\bar{h}|^2}, \quad (23)$$

where $q/p = \mathrm{e}^{-2\mathrm{i}\beta}$ with $|p|^2+|q|^2=1$ and β is one of the three CKM angles.

From Fig. 3(b), one can find the central values of the CP-violation parameters:

$$a_{\epsilon'}=0.31,\ a_{\epsilon+\epsilon'}=0.94,\ a_{\bar{\epsilon}'}=0.93,\ a_{\epsilon+\bar{\epsilon}'}=0.32, \quad (24)$$

for $\alpha=100^\circ$.

For $\overline{\mathrm{B}}^0 \to \mathrm{a}_0^0\pi^0$, $\mathrm{a}_0^-\pi^0$, and $\mathrm{B}^- \to \mathrm{a}_0^0\pi^-$ decays, the α-dependence of their direct CP asymmetries is shown in Fig. 3(a). Although the branching ratio of $\mathrm{B}^- \to \mathrm{a}_0^0\pi^-$ decay is the largest one among the considered channels, its direct CP asymmetry is the smallest one, about 14% for a fixed $\alpha = 100^\circ$. For $\overline{\mathrm{B}}^0 \to \mathrm{a}_0^0(980)\pi^0$ and $\mathrm{B}^- \to \mathrm{a}_0^-(980)\pi^0$ decays, their CP asymmetries can be large, about (70–80)% for $\alpha=100^\circ$, but the corresponding branching ratios are small,around $(4–5)\times10^{-7}$, and therefore it is difficult to measure them.

5 Conclusion

In this paper, we calculate the branching ratios and CP-violating asymmetries of $\overline{\mathrm{B}}^0 \to \mathrm{a}_0^0\pi^0$, $\mathrm{a}_0^+\pi^-$, $\mathrm{a}_0^-\pi^+$, and $\mathrm{B}^- \to \mathrm{a}_0^0\pi^-$, $\mathrm{a}_0^-\pi^0$ decays in the pQCD factorization approach by identifying $\mathrm{a}_0(980)$ as the 2-quark content. Based on the analytical calculations and numerical results, we find that:

1) The pQCD predictions for the branching ratios are around $(0.4-2.8)\times10^{-6}$, consistent with currently available experimental upper limits. The 2-quark model supposition of $\mathrm{a}_0(980)$ can not be ruled out by the current experimental data.

2) Although the CP asymmetries of $\overline{\mathrm{B}}^0 \to \mathrm{a}_0^0(980)\pi^0$ and $\mathrm{B}^- \to \mathrm{a}_0^-(980)\pi^0$ decays can be large, about (70–80)%, it is still difficult to measure them due to their small branching ratios.

Zhang Zhi-Qing would like to thank Cheng Hai-Yang and Wang Wei for their helpful discussions.

References

1 CHENG H Y, YANG K C. Phys. Rev. D, 2005, **71**: 054020; CHENG H Y, CHUA C K, YANG K C. Phys. Rev. D, 2006, **73**: 014017
2 CHENG C H. Phys. Rev. D, 2003,**67**: 014012; CHENG C H. Phys. Rev. D, 2003, **67**: 094011
3 WANG W et al. Phys. Rev. D, 2006, **74**: 114010
4 ZHANG Z Q, XIAO Z J. Chin. Phys. C, 2009, **33**: 508
5 SHEN Y L et al. Eur. Phys. J. C, 2007, **50**: 877–887
6 DU D S, LI J W, YANG M Z. Phys. Lett. B, 2005, **619**: 105; YANG M Z. Phys. Rev. D, 2006, **73**: 034027; YANG M Z. Mod. Phys. Lett. A, 2006, **21**: 1625
7 Garmash A et al (Belle collaboration). Phys. Rev. D, 2002, **65**: 092005
8 Aubert B et al (BaBar collaboration). Phys. Rev. D, 2004, **70**: 092001
9 Garmash A et al (Belle collaboration). Phys. Rev. D, 2005, **71**: 092003; Dragic J, talk presented at the HEP2005 Europhysics Conference in Lisboa, Portugal, July 21–27, 2005
10 Aubert B et al (BaBar collaboration). Phys. Rev. D, 2006, **73**: 031101; Phys. Rev. Lett., 2005, **94**: 041802; Aubert B et al (BaBar collaboration). Phys. Rev. D, 2005, **72**: 072003
11 Aubert B et al (BaBar collaboration). Phys. Rev. D, 2004, **70**: 111102; Phys. Rev. D, 2007, **75**: 111102
12 Delepine D, J L Lucio M, Ramirez C A. Eur. Phys. J. C, 2006, **45**: 693–700
13 Aubert B et al (BaBar collaboration). hep-ex/0607064; Aubert B et al (BaBar collaboration). Phys. Rev. D, 2008, **77**: 011101
14 Amsler C et al (Particle Data Group). Phys. Lett. B, **667**: 1
15 Close F E, Törnqvist N A et al. J. Phys. G, 2002, **28**: R249
16 Törnqvist N A. Phys. Rev. Lett., 1982, **49**: 624
17 Jaffe G L. Phys. Rev. D, 1977, **15**: 267; Phys. Rev. D, 1977, **15**: 281; Kataev A L. Phys. Atom. Nucl., 2005, **68**: 567; Vijande A, Valcarce A, Fernandez F, Silvestre-Brac B. Phys. Rev. D, 2005, **72**: 034025
18 Weinstein J, Isgur N. Phys. Rev. Lett. , 1982, **48**: 659; Phys. Rev. D, 1983, **27**: 588 ; Locher M P et al. Eur. Phys. J. C, 1998, **4**: 317
19 Baru V et al. Phys. Lett. B, 2004, **586**: 53
20 LI H N. Phys. Rev. D, 2002, **66**: 094010
21 LI H N, Tseng B. Phys. Rev. D, 1998, **57**: 443
22 Buchalla G, Buras A J, Lautenbacher M E. Rev. Mod. Phys., 1996, **68**: 1125
23 Ali A, Kramer G, LÜ C D. Phys. Rev. D, 1998, **58**: 094009