Final-state interactions and s-quark helicity conservation in $B\rightarrow J/\psi K^*$

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The latest BaBar Collaboration measurement has confirmed substantial strong phases for the $B\rightarrow J/\psi K^*$ decay amplitudes, implying violation of factorization in this decay mode. In the absence of a polarization measurement of a lepton pair from J/ψ, however, the relative phases of the spin amplitudes still have a twofold ambiguity. In one set of the allowed phases the s-quark helicity is conserved approximately despite final-state interactions. In the other set, the s-quark helicity is badly violated by long-distance interactions. We cannot rule out the latter since the validity of perturbative QCD is questionable for this decay. We examine the large final-state interactions with a statistical model. Toward a resolution of the ambiguity without a lepton polarization measurement, we discuss the relevance of other $B\rightarrow 1^-1^-$ decay modes that involve the same feature.

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The BaBar Collaboration [1] has shown, in line with the Collider Detector at Fermilab (CDF) [2], that substantial strong phases are generated in the decay $B\rightarrow J/\psi K^*$. It is not surprising since the argument of short-distance dominance does not hold for this decay according to perturbative QCD study [3,4] of final-state interactions (FSI). Beneke *et al.* [3] question short-distance dominance on the basis of the size of J/ψ, while Cheng and Yang [5] actually find a large correction to factorization from a higher twist in the case of $B\rightarrow J/\psi K$.

Since the experiment does not measure the polarization of the lepton pair from J/ψ, there is a twofold ambiguity left in the relative strong phases of three spin amplitudes. Specifically, the relative phase between two transverse spin amplitudes is determined only up to π. Two allowed sets of phases are physically inequivalent and correspond to very different physics for the FSI.

The decay $B\rightarrow J/\psi K^*$ occurs predominantly by the quark process $\overline{b}\rightarrow\overline{c}_L c_L \overline{s}_L$ through the tree decay operators. In the perturbative picture, $\overline{s}_L$ would pick a u/d quark to form the final K^*. If $\overline{s}_L$ maintains its helicity, K^* cannot be in helicity -1. Consequently, we expect naively that the helicity $+1$ amplitudes should dominate over the helicity -1 amplitude. The twofold ambiguity left in the analysis [1,2,6] corresponds to dominance of helicity $+1$ or -1. If helicity $+1$ dominates, factorization may still be a decent approximation apart from the strong phases. But if helicity -1 dominates, long-distance FSI are large and flip the s-quark helicity. Therefore it is important to resolve this ambiguity in order to test the robustness of factorization and to understand the nature of FSI in general.

When FSI are large, we have no reliable way to compute individual strong phases. A statistical model [7] was developed to fill the void. In this model large phases and helicity violation can occur if color suppression is severe and rescattering is strong enough in $B\rightarrow J/\psi K^*$. Guided by the statistical model, we look for decay modes that share the same feature. Aside from $B_s\rightarrow J/\psi\phi$, we propose measurement of $B\rightarrow\psi(2s)K^*$, $B^-\rightarrow D^{0*}\rho^-$, and other $B\rightarrow 1^-1^-$ modes. Although final resolution of the ambiguity requires lepton polarization measurement in the future, measurement of the spin amplitudes of these decays will help us to understand the FSI better.

Three spin amplitudes $A_{\parallel,\perp,0}$ of $B\rightarrow J/\psi K^*$ are related to the helicity amplitudes $H_{\pm1,0}$ by [8,9] $A_\parallel=(H_{+1}+H_{-1})/\sqrt{2}$, $A_\perp=(H_{+1}-H_{-1})/\sqrt{2}$, $A_0=H_0$, where the helicity amplitudes are defined in the rest frame of B by $H_\lambda=\langle J/\psi(\lambda),K^*(\lambda)|H|B\rangle$. We follow the original sign convention of Dighe *et al.* [8].

The relative magnitudes of $A_{\parallel,\perp,0}$ for $B(q\overline{b})\rightarrow J/\psi K^*$ are given by the BaBar Collaboration [1] as $|A_0|^2=0.597\pm0.028\pm0.024$, $|A_\perp|^2=0.160\pm0.032\pm0.014$, $|A_\parallel|^2=1-|A_0|^2-|A_\perp|^2$. The phases are quoted in radians as

$$\phi_\perp\equiv\arg(A_\perp A_0^*)=-0.17\pm0.16\pm0.07,$$

$$\phi_\parallel\equiv\arg(A_\parallel A_0^*)=2.50\pm0.20\pm0.08\ \ [\text{solution I}]. \tag{1}$$

However, since measurement of the interference terms in the angular distribution is limited to $\mathrm{Re}(A_\parallel A_0^*)$, $\mathrm{Im}(A_\perp A_0^*)$, and $\mathrm{Im}(A_\perp A_\parallel^*)$, there exists an ambiguity of [10,11] $\phi_\parallel\leftrightarrow-\phi_\parallel$, $\phi_\perp\leftrightarrow\pi-\phi_\perp$, $\phi_\perp-\phi_\parallel\leftrightarrow\pi-(\phi_\perp-\phi_\parallel)$. Therefore, another set of values,

$$\phi_\perp=\arg(A_\perp A_0^*)=-2.97\pm0.16\pm0.07,$$

$$\phi_\parallel=\arg(A_\parallel A_0^*)=-2.50\pm0.20\pm0.08\ [\text{solution II}], \tag{2}$$

is also allowed when $\phi_{\perp,\parallel}$ is chosen in $(-\pi,\pi)$. Since $|A_\parallel|\approx|A_\perp|$ and $\phi_\parallel-\phi_\perp\approx\pi$ or 0, two sets of phases in Eqs. (1) and (2), referred to as solutions I and II, mean roughly $A_\parallel\approx\mp A_\perp$. That is, either $|H_{+1}|\ll|H_{-1}|$ (solution I) or $|H_{+1}|\gg|H_{-1}|$ (solution II). To be quantitative, we obtain in terms of the helicity amplitudes $|H_{\pm1}/H_{\mp1}|=0.26\pm0.14$ [solution I/II], where the upper and lower signs in the subscripts of the helicity amplitudes correspond to solutions I and II, respectively. Our concern is this twofold ambiguity.

In the decay $B(q\overline{b})\rightarrow J/\psi(c\overline{c})K^*(q\overline{s})$ the $\overline{s}$ quark is produced in helicity $+\frac{1}{2}$ by weak interaction in the limit of $m_s\rightarrow0$. It would maintain its helicity throughout strong interaction if $m_s=0$. Therefore, when the $\overline{s}$ quark picks up q (u

or d), they form K^* in helicity either $+1$ or 0, not in helicity -1. Within perturbative QCD this argument is valid as long as we ignore corrections of m_s/E and $|\mathbf{p}_t|/E$, and higher configurations of K^* such as $\bar{s}q\bar{q}q$ and $\bar{s}qg$. If the FSI are entirely of short distances, therefore, the decay amplitudes should obey the selection rule $H_{-1}\simeq 0$ for $B(q\bar{b})\to J/\psi K^*$, namely,

$$A_{\parallel}\simeq +A_{\perp} \text{ for } B(q\bar{b})\to J/\psi K^*. \tag{3}$$

Equation (3) means for both magnitude and phase. Similarly, $H_{+1}\simeq 0$ or $A_{\parallel}\simeq -A_{\perp}$ for $\overline{B}(\bar{q}b)\to J/\psi \overline{K}^*$. Solution II is not far from this prediction. However, the validity of the perturbative QCD argument is suspect for the decay $B\to J/\psi K^*$ since the size of J/ψ is $O(1/\alpha_s m_c)$ instead of $O(1/m_c)$ [3]. If long-distance FSI are important, the s-quark helicity can easily be flipped through meson-meson rescattering in the final state. Then solution I cannot be ruled out.

The $B\to J/\psi K^*$ amplitudes were calculated in the past mostly with factorization combined with extrapolation or scaling rules of form factors [12–14]. Those calculations naturally predicted $|H_{+1}|>|H_{-1}|$ for $B\to J/\psi K^*$. Since factorization leads to zero strong phases, $|\phi_{\parallel}|-\pi=37°\pm 11°\pm 4°$ is a measure of the deviation from factorization if solution I is chosen.[1]

The case for solution II may look strong. However, there is no firm theoretical basis for the validity of factorization for $B\to J/\psi K^*$. Indeed, the observed strong phases are larger than what we would normally expect for the short-distance QCD correction to factorization. Furthermore, the Belle Collaboration [16] very recently made positive identification of the $\overline{B}^0\to D^{(*)0}X^0$ decay modes. The branching fraction of $\overline{B}^0\to D^0\pi^0$ is now much larger than the tight upper bound that was set by the CLEO Collaboration [17,18] and advocated by factorization calculation. Those decay modes share one common feature with $B\to J/\psi K^*$. We therefore proceed to explore the possibility of solution I, i.e., large violation of s-quark helicity conservation due to large long-distance FSI.

We look for the origin of the fairly large strong phase which is three standard deviations away from zero. One characteristic of the decay $B\to J/\psi K^*$ may be relevant to the large phase. That is, this decay is a color-suppressed process.[2] A statistical model [7] was proposed for the strong phases of B decay for which the short-distance argument fails. The model predicts that the more a decay process is suppressed, the larger its strong phase can be. The reason is as follows: In a suppressed process of a given decay operator, B tends to decay first into unsuppressed decay channels and then rescatters into its final state by FSI. In $B\to J/\psi K^*$, the B meson decays first into color-allowed on-shell states such as $\overline{D}^{(*)}D_s^{(*)}$ and then turns into $J/\psi K^*$ through the quark-rearrangement scattering of strong interactions (crossed quark-line diagram). Such two-step processes are likely to dominate over direct color-suppressed transition. If so, these on-shell intermediate states tend to generate larger strong phases for color-suppressed amplitudes than for color-allowed amplitudes dominated by the direct transition. The same picture was advocated independently by Rosner in his qualitative argument [19].

However, computing individual strong phases is a formidable task when so many decay channels are open and interact with each other through long-distance FSI. The statistical model quantifies the range of likely values ($-\overline{\delta}\leqslant\delta\leqslant\overline{\delta}$) for a strong phase δ in terms of two parameters, the degree of suppression ($1/\rho$) and the strengh of FSI (τ), by the relation [7]

$$\tan^2\overline{\delta}=\tau^2(\rho^2-\tau^2)/(1-\rho^2\tau^2)\,, \tag{4}$$

which is valid for $\tau^2<\rho^2<1/\tau^2$. Outside this region of ρ and τ, the right-hand side of Eq. (4) is negative. In this case suppression is so severe ($1/\rho^2<\tau^2$) and/or rescattering transition between J/ψ and $\overline{D}^{(*)}D_s^{(*)}$ is so strong ($\tau^2>\rho^2$) that any value is possible for δ.

For the suppression parameter we expect $1/\rho=O(1/N_c)$ in our case. Although color suppression does not always work as we expect, $1/\rho^2=O(1/N_c^2)$ is in line with experiment. Let us choose $1/\rho^2\simeq 1/20$ by comparing $B(B^+\to J/\psi K^{*+})=(1.48\pm 0.27)\times 10^{-3}$ with $B(B^+\to\overline{D}^{*0}D_s^{*+})=(2.7\pm 1.0)\times 10^{-2}$ [18]. To determine the value of τ, we need the strength of the $J/\psi K^*$ reaction which is little known. For the total cross section, the strength is controlled by Pomeron exchange. Since it is generated by two-gluon exchange in the standard lore, one possible estimate is $\sigma_{\rm tot}^{J/\psi K^*}\approx[\alpha_s(E)/\alpha_s(\Lambda_{QCD})]^2\sigma_{\rm tot}^{\pi\pi}$ where $E=\frac{1}{2}(4m_D^2-m_{J/\psi}^2)^{1/2}\simeq 1$ GeV is the binding of J/ψ. This means that energy transfer of $O(E)$ is needed to break up J/ψ by hitting it with a gluon. With this reasoning we expect rescattering of J/ψ to be less strong than that of $\pi\pi$ and πK. If we choose tentatively $\sigma_{\rm tot}^{J/\psi K^*}\simeq 0.5\times\sigma_{\rm tot}^{\pi\pi}$, we find $\tau^2\simeq 0.09$ [7]. For $\rho^2\simeq 20$ and $\tau^2\simeq 0.09$ ($\rho^2\tau^2\simeq 1.8$), the right-hand side of Eq. (4) is negative so that δ can take any value, as remarked above. Physically, the cascade processes $B\to\overline{D}^{(*)}D_s^{(*)}\to J/\psi K^*$ dominate over the direct $B\to J/\psi K^*$ transition in this case. When this happens, there is no reason to expect that the s-quark helicity is conserved. Then it is not impossible that $A_{\parallel}$ and $A_{\perp}$ will acquire a relative phase large enough to flip their relative sign. On the other hand, $\sigma_{tot}^{J/\psi K^*}$ may well be much smaller than our estimate above. If it is one-tenth of $\sigma_{tot}^{\pi\pi}$, for instance, the strong phases of $B\to J/\psi K^*$ should be in the range smaller than 35° or so. If this is the case, the direct decay still dominates and the s-quark helicity is approximately conserved.

Because of uncertainties in the strong interaction physics involved, we are unable to make a convincing estimate for the likely values of strong phases of $B\to J/\psi K^*$. We can say

[1] It was recently pointed out [15] that the s-quark helicity conservation is consistent with the decay rate ratio $\Gamma(B\to\gamma K^*)/\Gamma(B\to\gamma X_s)$. Without additional theoretical input, however, experiments on the rates alone cannot conclude $h=+1$ dominance.

[2] We mean as usual an $O(1/N_c)$ contribution from the dominant operator $(\bar{b}c)(\bar{c}s)$ and an $O(1)$ contribution from the suppressed operator $(\bar{b}s)(\bar{c}c)$.

only that very large strong phases are possible for this decay. We therefore look for other B decay modes which will help in resolving the issue.

If long-distance FSI are large in $B\to J/\psi K^*$, the pattern of $|A_\parallel|\simeq|A_\perp|$, $\phi_\parallel\simeq\phi_\perp$ (modulo π) must be interpreted as an accident. Measurement of the spin amplitudes for $B\to\psi(2s)K^*$ will shed light on this case: If the same pattern appears in $B\to\psi(2s)K^*$, we will favor conservation of s-quark helicity in the sense that two accidents are more unlikely to occur than one.

The decay $B_s\to J/\psi\phi$ is identical to $B\to J/\psi K^*$ up to $d/u\leftrightarrow s$. At present we know from the CDF Collaboration [2] that $|A_0|=0.78\pm0.09\pm0.01$, $|A_\parallel|=0.41\pm0.23\pm0.05$, $|A_\perp|=0.48\pm0.20\pm0.04$, and for the phases $\phi_\parallel=\pm1.1\pm1.3\pm0.2$. Nothing is known for $\phi_\perp$. At present the uncertainty of $\phi_\parallel$ is too large to make any statement. As the experimental uncertainties become smaller, we should watch whether $|A_\parallel|\approx|A_\perp|$ stands or not, and whether $\phi_\parallel-\phi_\perp$ converges to zero (modulo π) or not. If both happen, we can make a stronger case for s-quark helicity conservation. If either relation is badly violated, it will cast doubt on the s-quark helicity conservation in $B\to J/\psi K^*$. A similar test of the d-quark helicity conservation in $B\to J/\psi\rho$ will serve the same purpose.

The decay mode $B^-\to D^{*0}\rho^-$ provides us with an interesting opportunity. The decay $\overline{B}^0\to D^{*+}\rho^-$ is a color-allowed process ($b\to c_L\overline{u_L d_L}$) for which factorization is expected to work well. Here the dominant decay operator is the tree operator $(\overline{c}b)(\overline{d}u)$. In this decay ρ^- is formed by the collinear $d_L\overline{u_L}$ from the weak current so that the helicity of ρ^- must be 0, not ±1. In fact, experiment has confirmed the dominance of $h=0$; $|A_0|^2/\Sigma|A_i|^2=0.93\pm0.05\pm0.05$ [20]. Since there is only one spin amplitude of significant magnitude, one cannot measure a strong phase in this mode. However, the validity of perturbative QCD leaves us little doubt about the u/d-quark helicity conservation and the smallness of the strong phase in $\overline{B}^0\to D^{*+}\rho^-$.

In contrast, the decay $B^-\to D^{*0}\rho^-$ can occur through a color-suppressed process as well since the fast d_L from the weak current can pick up the spectator $\overline{u}$ instead of $\overline{u_L}$ from the current. Relative to the dominant process, this process is not only color suppressed but also power suppressed through the ρ^- wave function [3]. Despite the expected double suppression, this amplitude is not so small in reality and shifts the square root of the rate by about one-third from that for the color-allowed process alone [18]:

$$|\Gamma(B^-\to D^{*0}\rho^-)/\Gamma(\overline{B}^0\to D^{*+}\rho^-)|^{1/2}=1.36\pm0.18. \quad (5)$$

The left-hand side can be expressed as $|1+0.79(a_2/a_1)|$ in terms of the color-allowed and -suppressed amplitudes a_1 and a_2, in the notation of Bauer, Stech, and Wirbel [21]. If factorization is a good approximation, $a_{1,2}$ are real and a_2 is very small ($0<a_2/a_1<0.15$) although its precise value is sensitive to cancellation between two Wilson coefficients. The sizable deviation from unity in the right-hand side of Eq. (5) indicates that the color-suppressed portion of the $B^-\to D^{*0}\rho^-$ amplitude exceeds the magnitude predicted by factorization.[3] It can accommodate any large phase for a_2/a_1. Therefore we should test whether this color-suppressed portion of the amplitude has a large strong phase or not.

Since ρ^- is dominantly in helicity 0 in the color-allowed $B^-\to D^{*0}\rho^-$ decay, the helicity amplitudes $H_{\pm1}$ can arise mostly from the color-suppressed decay, if at all. Since ρ^- is made of d_L from weak current and the spectator $\overline{u}$ in this case, the ρ^- helicity would be either -1 or 0, not $+1$. In this respect, the situation is parallel to $B\to J/\psi K^*$ up to charge conjugation. The other current quark $\overline{u_L}$ enters D^{*0} so that the helicity of D^{*0} must be either $+1$ or 0 depending on the helicity of c. Consequently, the u/d-quark helicity conservation would allow only longitudinal meson helicities even in the color-suppressed process if short-distance (SD) FSI dominate:

$$H_{\pm1}\simeq0 \quad \text{for} \quad B^-\to D^{*0}\rho^-(\text{SD}). \quad (6)$$

If FSI are entirely of short distances, the expected accuracy of Eq. (6) should be even higher than that of the s-quark helicity conservation. Needless to say, this prediction results in all factorization calculations if light-quark helicity conservation is implemented for the form factors. If the pattern of Eq. (6), namely, $|A_0|\simeq1$, emerges in $B^-\to D^{*0}\rho^-$, it will indicate short-distance dominance even for its color-suppressed a_2 amplitude and therefore give indirect support to the s-quark helicity conservation in $B\to J/\psi K^*$. For determination of $|A_0|$, we do not need full measurement of the transversity angular distribution.

Finally, we point out that we shall be able to carry out the same test with the color-suppressed decay $\overline{B}^0\to D^{*0}\omega$. The Belle Collaboration very recently measured this decay branching [16] at a level much higher than anticipated. We may have a good chance to test directly with $\overline{B}^0\to D^{*0}\rho^0$, which consists purely of the a_2 amplitude of $\overline{B}\to D^*\rho$.

We have examined the twofold ambiguity in determination of the spin amplitudes of $B\to J/\psi K^*$. One solution is consistent with approximate s-quark helicity conservation despite substantial strong phases, while the s-quark helicity conservation is badly violated in the other solution. Although the case for s-quark helicity conservation may look stronger to many theorists, a large violation is quite possible at present. Hence we have explored with a statistical model the possibility of large s-quark helicity violation and argued how measurement of $B\to\psi(2s)K^*$, $B\to J/\psi\phi$, $B^-\to D^{*0}\rho^-$, and $\overline{B}^0\to D^{*0}\omega/\rho^0$ will serve toward resolution of the issue.

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[3]Although Eq. (5) alone would allow destructive interference between a_1 and a_2, such a large value for $|a_2|$ would lead us to an unacceptably large branching fraction for $\overline{B}^0\to D^{*0}\rho^0$ by the $\Delta I=1$ sum rule.

sign conventions and the ambiguity in determination of the spin amplitudes. I acknowledge conversations with G. Burdman and R. N. Cahn. This work was supported in part by the Director, Office of Science, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098 and in part by the National Science Foundation under Grant PHY-95-14797.

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