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Mahiko Suzuki

Physics Division

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Mahiko Suzuki

Physics Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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

Mahiko Suzuki
Department of Physics and Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720

Abstract

The latest BaBar measurement has confirmed substantial strong phases for the $B \to J/\psi K^*$ decay amplitudes implying violation of factorization in this decay mode. In the absence of 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 conserves 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 validity of perturbative QCD is questionable for this decay. We examine the large final-state interactions with a statistical model. Toward resolution of the ambiguity without lepton polarization measurement, we discuss relevance of other $B \to 1^-1^-$ decay modes that involve the same feature.

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I. INTRODUCTION

The BaBar Collaboration [1] has shown in line with CDF [2] that substantial strong phases are generated in the decay $B \to J/\psi K^*$. 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 $B \to J/\psi K$.

Since the experiment does not measure 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 set of phases are physically inequivalent and correspond to very different physics for FSI.

The decay $B \to J/\psi K^*$ occurs dominantly by the quark process $\bar{b} \to \overline{c_L} c_L \overline{s_L}$ 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 robustness of factorization and to understand the nature of FSI in general.

When FSI is 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 $B \to J/\psi K^*$. Guided by the statistical model, we look for the decay modes which share the same feature. Aside from $B_s \to J/\psi\phi$, we propose measurement of $B \to \psi(2s)K^*$, $B^- \to D^{0*}\rho^-$, and other $B \to 1^-1^-$ modes. Though final resolution of the ambiguity requires lepton polarization measurement in some future, measurement of the spin amplitudes of these decay will help us to understand the FSI better.

II. EXPERIMENT

Three spin amplitudes $A_{\|,\perp,0}$ of $B \to J/\psi K^*$ are related to helicity amplitudes $H_{\pm 1,0}$ by [8,9]:

$$A_{\|} = (H_{+1} + H_{-1})/\sqrt{2}, \;\; A_{\perp} = (H_{+1} - H_{-1})/\sqrt{2}, \;\; A_0 = H_0, \tag{1}$$

where helicity amplitudes are defined in the rest frame of B by

$$H_\lambda = \langle J/\psi(\lambda), K^*(\lambda)|H|B\rangle. \tag{2}$$

We follow the original sign convention of Dighe et al [8].

Relative magnitudes of $A_{\|,\perp,0}$ for $B(q\bar{b}) \to J/\psi K^*$ are given by BaBar [1] as

$$
\begin{aligned}
|A_0|^2 &= 0.597 \pm 0.028 \pm 0.024 \\
|A_\perp|^2 &= 0.160 \pm 0.032 \pm 0.014 \\
|A_\parallel|^2 &= 1 - |A_0|^2 - |A_\perp|^2.
\end{aligned} \tag{3}
$$

The phases are quoted in radians as

$$
\begin{aligned}
\phi_\perp &\equiv \arg(A_\perp A_0^*) = -0.17 \pm 0.16 \pm 0.07, \\
\phi_\parallel &\equiv \arg(A_\parallel A_0^*) = 2.50 \pm 0.20 \pm 0.08. \quad \text{[Solution I]}
\end{aligned} \tag{4}
$$

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]

$$
\begin{aligned}
\phi_\parallel &\leftrightarrow -\phi_\parallel \\
\phi_\perp &\leftrightarrow \pi - \phi_\perp \\
\phi_\perp - \phi_\parallel &\leftrightarrow \pi - (\phi_\perp - \phi_\parallel).
\end{aligned} \tag{5}
$$

Therefore, another set of values,

$$
\begin{aligned}
\phi_\perp &= \arg(A_\perp A_0^*) = -2.97 \pm 0.16 \pm 0.07, \\
\phi_\parallel &= \arg(A_\parallel A_0^*) = -2.50 \pm 0.20 \pm 0.08, \quad \text{[Solution II]}
\end{aligned} \tag{6}
$$

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. (4) and (6), referred to as Solution I and II, mean roughly

$$
A_\parallel \approx \mp A_\perp. \tag{7}
$$

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,

$$
|H_{\pm 1}/H_{\mp 1}| = 0.26 \pm 0.14, \ \text{[Solution I/II]} \tag{8}
$$

where the upper and lower signs in the subscripts of the helicity amplitudes correspond to Solution I and II, respectively. Our concern is on this twofold ambiguity.

III. LIGHT-QUARK HELICITY CONSERVATION

In the decay $B(q\bar{b}) \to J/\psi(c\bar{c})K^*(q\bar{s})$ the $\bar{s}$-quark is produced in helicity $+\frac{1}{2}$ by weak interaction in the limit of $m_s \to 0$. It would maintain its helicity throughout strong interaction if $m_s = 0$. Therefore, when the $\bar{s}$-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 FSI is entirely of short distances, therefore, the decay amplitudes should obey the selection rule;

$$
H_{-1} \simeq 0 \ \text{ for } B(q\bar{b}) \to J/\psi K^*, \tag{9}
$$

namely,

$$A_{\parallel} \simeq +A_{\perp} \text{ for } B(q\bar{b}) \to J/\psi K^*. \tag{10}$$

Eq. (10) 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, 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 is important, the s-quark helicity can be easily 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, $|\phi_{\parallel}| - \pi = 37^\circ \pm 11^\circ \pm 4^\circ$ is a measure of deviation from factorization if Solution I is chosen.[1]

IV. CHARM QUARK SPIN CONSERVATION

The relative magnitude of A_0 to $A_{\parallel,\perp}$ depends on $c\bar{c}$ of J/ψ. We point out that the BaBar data can be reproduced by a very simple model if the s-quark helicity conserves.

If the c-quark were light, $c_L\bar{c}_L$ would produce J/ψ only in $h = 0$ state so that $|A_0| = 1$. This limit obviously disagrees with experiment. Heavy charm quark is certainly a better approximation. In this case a $c_L\bar{c}_L$ pair is produced collinearly by weak interaction and forms J/ψ. If the relevant strong interaction is much softer than $O(m_c)$, spin flip is suppressed for c and $\bar{c}$ by $1/m_c$. Then the final J/ψ spin state is obtained by projection of the collinear $c_L\bar{c}_L$ onto ${}^3S_1$. A straightforward computation leads us to

$$|c\bar{c}(1^{--})\rangle = N\Big[(1+\Delta^2)\sqrt{\frac{1}{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle) + \sqrt{2}\Delta(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)\Big], \tag{11}$$

where the up and down arrows represent helicity $\pm\frac{1}{2}$, the first and second entries refer to c and $\bar{c}$, respectively, $N = 1/[(1+\Delta^2)^2 + 4\Delta^2]^{1/2}$ is the normalization, and $\Delta = [(E_p - |\mathbf{p}| + m_c)/(E_p + |\mathbf{p}| + m_c)]$. We have made the approximation that the J/ψ binding is much smaller than m_c and therefore $\mathbf{p}_c \simeq \mathbf{p}_{\bar{c}} \simeq \frac{1}{2}\mathbf{p}_{J/\psi}(= \mathbf{p})$. If the $\bar{s}_L$-quark helicity is conserved, $K^*(\bar{s}_L q)$ is produced in $h = 0$ or -1 with 1 to 2 ratio in probability since helicity of q is $+\frac{1}{2}$ or $-\frac{1}{2}$ in equal probability. Combining the spin states of J/ψ and K^*, we obtain the ratios of $|A_{\parallel,\perp,0}|^2$:

$$|A_0|^2 : \frac{1}{2}|A_{\parallel} + A_{\perp}|^2 : \frac{1}{2}|A_{\parallel} - A_{\perp}|^2 = N^2(1+\Delta^2)^2 : 4N^2\Delta^2 : 0. \tag{12}$$

The right-hand side is fairly insensitive to m_c. For $m_c \simeq 1.5$ GeV, we have $\Delta^2 \simeq 0.37$ and

---

[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, experiment on the rates alone cannot conclude $h = +1$ dominance.

$$|A_0|^2 \simeq 0.56 \tag{13}$$

as compared with $0.597 \pm 0.028 \pm 0.024$ [1]. Note that this model is valid even in the presence of FSI as long as s-quark helicity and charm quark spins are both conserved. Despite extreme simplicity of the model, it gives better agreement with experiment than many of the elaborate factorization calculations ($|A_0|^2$ in the range of $0.07 \sim 0.59$) tabulated in Ref. [12–14]. While the agreement may be fortuitous, one may consider it as another support for Solution II over Solution I, namely, the s-quark helicity conservation.

The case for Solution II may look strong. However, there is no firm theoretical basis for 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 CLEO [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 for chance of Solution I, *i.e.,* large violation of s-quark helicity conservation due to large long-distance FSI.

V. STATISTICAL MODEL OF STRONG PHASES

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, those 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 ($-\overline{\delta} \leq \delta \leq \overline{\delta}$) for a strong phase δ in terms of two parameters, degree of suppression ($1/\rho$) and strengh of FSI (τ), by the relation [7]

$$\tan^2 \overline{\delta} = \frac{\tau^2(\rho^2 - \tau^2)}{1 - \rho^2 \tau^2}, \tag{14}$$

---

[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 $(\bar{b}s)(\bar{c}c)$.

which is valid for $\tau^2 < \rho^2 < 1/\tau^2$. Outside this region of ρ and τ, the right-hand side of Eq. (14) 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. Though 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 strength of $J/\psi K^*$ 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 $E = \frac{1}{2}\sqrt{4m_D^2 - m_{J/\psi}^2} \simeq$ 1 GeV is the binding of J/ψ. It means that energy transfer of $O(E)$ is needed to break up J/ψ by hitting 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. (14) 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 conserves. Then it is not impossible that $A_\parallel$ and $A_\perp$ 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 approximately conserves.

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

VI. SPIN AMPLITUDES OF OTHER $B \to V_1 V_2$ MODES

If long-distance FSI is large in $B \to J/\psi K^*$, the pattern of

$$\begin{aligned} |A_\parallel| &\simeq |A_\perp| \\ \phi_\parallel &\simeq \phi_\perp \text{ (modulo } \pi). \end{aligned} \tag{15}$$

must be interpreted as an accident. Measurement of the spin amplitudes for $B \to \psi(2s)K^*$ will shed a light in 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 rarer 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 CDF [2]

$$\begin{aligned} |A_0| &= 0.78 \pm 0.09 \pm 0.01 \\ |A_\parallel| &= 0.41 \pm 0.23 \pm 0.05 \\ |A_\perp| &= 0.48 \pm 0.20 \pm 0.04, \end{aligned} \tag{16}$$

and for the phases

$$\phi_{\|} = \pm 1.1 \pm 1.3 \pm 0.2, \tag{17}$$

Nothing is known for $\phi_\perp$. At present the uncertainty of $\phi_{\|}$ is too large to make any statement. As the experimental uncertainties become smaller, we should watch whether $|A_{\|}| \approx |A_\perp|$ stands or not, and whether $\phi_{\|} - \phi_\perp$ 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 for the same purpose.

The decay mode $B^- \to D^{*0}\rho^-$ provides us 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 helicity of ρ^- must be 0, not ± 1. In fact, experiment confirmed dominance of $h = 0$; $|A_0|^2/\sum |A_i|^2 = 0.93 \pm 0.05 \pm 0.05$ [20]. Since there is only one spin amplitude of significant magnitude, one cannot measure a strong phase in this mode. However, 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 the $\overline{u}_L$ 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 square root of the rate by about one third from the color-allowed process alone [18]:

$$|\Gamma(B^- \to D^{*0}\rho^-)/\Gamma(\overline{B}^0 \to D^{*+}\rho^-)|^{1/2} = 1.36 \pm 0.18. \tag{18}$$

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 ($0 < a_2/a_1 < 0.15$) though its precise value is sensitive to cancellation between two Wilson coefficients. The sizable deviation from unity in the right-hand side of Eq. (18) 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 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 $H_{\pm 1}$ 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 helicity of D^{*0} must be either $+1$ or 0 depending on 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 FSI dominates:

---

[3]Although Eq. (18) 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.

$$H_{\pm 1} \simeq 0 \text{ for } B^- \to D^{*0}\rho^- \text{ (SD)}. \tag{19}$$

If FSI is entirely of short distances, the expected accuracy of Eq. (19) should be even higher than that of the s-quark helicity conservation. Needless to say that this prediction result in all factorization calculations if light-quark helicity conservation is implemented for form factors. If the pattern of Eq. (19), namely, $|A_0| \simeq 1$ emerges in $B^- \to D^{*0}\rho^-$, it will indicate short-distance dominance even for its color-suppressed a_2 amplitude and therefore give an 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 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 $\overline{B} \to D^*\rho$.

VII. SUMMARY

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. Though 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 the 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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Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road ♦ Berkeley, California 94720

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