Search for Factorization-Suppressed $B \to \chi_cK^{(*)}$ Decays

We search for the factorization-suppressed decays $B \rightarrow \chi_{c0}K^{(*)}$ and $B \rightarrow \chi_{c2}K^{(*)}$, with $\chi_{c0}$ and $\chi_{c2}$ decaying into $J/\psi\gamma$, using a sample of $124 \times 10^6$ $B\bar{B}$ events collected with the BABAR detector at the PRL 94, 171801 (2005) PHYSICAL REVIEW LETTERS week ending 6 MAY 2005 171801-3
Nonleptonic decays of heavy mesons are not easily described because the process involves quarks whose hadronization is not yet well understood. The factorization hypothesis allows one to make some predictions [1] by assuming that a weak decay matrix element can be described as the product of two independent hadronic currents. Under the factorization hypothesis, $B \to c\bar{c}K^{(*)}$ decays are allowed when the $c\bar{c}$ pair hadronizes to $J/\psi$, $\psi(2S)$, or $X_{c1}$, but are suppressed when the $c\bar{c}$ pair hadronizes to $X_{c0}$ or $X_{c2}$ [2]. Here, $K^{(*)}$ represents either $K$ or $K^*$. In the lowest-order heavy quark effective theory, there is no $J \geq 2$ current to create the tensor $X_{c2}$ from the vacuum. The decay rate to the scalar $X_{c0}$ is zero due to charge conjugation invariance [3].

Belle has recently observed $B^+ \to X_{c0}K^+$ decays with a branching fraction (BF) of $(6.0^{+2.1}_{-1.8} \pm 1.1) \times 10^{-4}$ [4] using $X_{c0}$ decays to $\pi^+\pi^-$ or $K^+K^-$. BABAR has confirmed the observation using the same decays with a branching fraction of $(2.7 \pm 0.7) \times 10^{-4}$ [5], somewhat lower than, but compatible with, the Belle measurement. These results are of the same order of magnitude as the BF of the decay $B^+ \to X_{c1}K^+$ and are surprisingly large given the expectation from factorization. Using the hadronic $X_{c0}$ decays, CLEO has obtained an upper limit on $B^0 \to X_{c0}K^0$ of $5.0 \times 10^{-4}$ [6]. Nonfactorizable contributions to $B^+ \to X_{c0}K^+$ decays due to the rescattering of intermediate charm states have been considered theoretically [7], and similar branching fractions are predicted for decays to $X_{c0}$ and $X_{c2}$. No predictions are available for $B$ decays to $X_{c(0.2)}K^*$, but the branching fraction of decays to $K^*$ may be expected to be similar to the branching fraction of decays to $K$. The measurement of $B \to X_{c(0.2)}K^{(*)}$ should improve our understanding of the limitations of factorization and of models that violate factorization.

In this Letter we report a search for the decays $B \to X_{cJ}K^{(*)}$, $J = 0, 2$, using the radiative decays $X_{cJ} \to J/\psi\gamma$, with branching fractions of $(1.18 \pm 0.14)\%$ and $(20.2 \pm 1.7)\%$, respectively [8]. Since the radiative branching fraction for the $X_{c0}$ decay (including subsequent $J/\psi$ decay to $\ell^+\ell^-$) is much smaller than the corresponding $\pi^+\pi^-$ or $K^+K^-$ branching fractions, the search for the $B^+ \to X_{c0}K^+$ decay is less sensitive than previous searches, but it is free from the interference with the nonresonant decays to three mesons that affect the latter. The data used in this analysis were obtained with the BABAR detector at the PEP-II storage ring, comprising an integrated luminosity of $112$ fb$^{-1}$ of data taken at the $Y(4S)$ resonance.

The BABAR detector is described elsewhere [9]. Surrounding the interaction point, a five-layer double-sided silicon vertex tracker (SVT) provides precise reconstruction of track angles and $B$-decay vertices. A 40-layer drift chamber (DCH) provides measurements of the transverse momenta of charged particles. An internally reflecting ring-imaging Cherenkov detector (DIRC) is used for particle identification (PID). A CsI(Tl) crystal electromagnetic calorimeter detects photons and electrons. The calorimeter is surrounded by a solenoidal magnet providing a 1 T field. The flux return is instrumented with resistive plate chambers used for muon and neutral-hadron identification.

The channels considered here are $B \to X_cK^{(*)}$ with $X_c \to J/\psi\gamma$ and $J/\psi \to \ell^+\ell^-$, where $\ell$ is $e$ or $\mu$. $K$ is $K^+$ or $K_{S}^0$ ($\to \pi^+\pi^-$), $K_{S}^0 \to K^+\pi^-$ or $K_{S}^0\pi^0$, $K^{(*)} \to \pi^0K^{(*)}$, and $\pi^0 \to \gamma\gamma$. Charge-conjugate modes are included implicitly throughout this Letter. Event selection is optimized by maximizing $\epsilon/\sqrt{N_b}$, where $\epsilon$ is the signal efficiency after all selection requirements and $N_b$ the number of background events, estimated with $Y(4S) \to B\bar{B}$ and $e^+e^- \to q\bar{q}$ Monte Carlo (MC) samples.

Candidate $J/\psi$ mesons are reconstructed from a pair of oppositely charged lepton candidates that form a good vertex. Muon (electron) candidates are identified with a neural-network (cut-based) selector and loose selection criteria. Electromagnetic depositions in the calorimeter in the polar-angle range $0.410 < \theta_{lab} < 2.409$ rad that are not associated with charged tracks have an energy larger than 30 MeV, and a shower shape consistent with a photon are taken as photon candidates. For $J/\psi \to e^+e^-$ decays, electron candidates are combined with nearby photon candidates in order to recover some of the energy lost through bremsstrahlung. The lepton-pair invariant mass must be in the range $2.95, 3.18$ GeV/c$^2$ for both lepton flavors. The small remaining background is mainly due to $J/\psi$ mesons not originating from $X_c$ decays.

We form $K_{S}^{0}$ candidates from oppositely charged tracks originating from a common vertex with invariant mass in the range $487, 510$ MeV/c$^2$. The $K_{S}^{0}$ flight length must be greater than 1 mm, and its direction in the plane perpendicular to the beam line must be within 0.2 rad of the $K_{S}^{0}$ momentum vector. Charged kaon candidates are identified with a likelihood selector, based on information from the DIRC, and $dE/dx$ in the SVT and in the DCH.

A $\phi^0$ candidate is formed from a pair of photon candidates with invariant mass in the interval $[117, 152]$ MeV/c$^2$ and momentum greater than 350 MeV/c. $K^*$ candidates are formed from $K\pi$ combinations with an invariant mass in the range $[0.85, 0.94]$ GeV/c$^2$.

The $J/\psi$, $K_{S}^{0}$, and $\phi^0$ candidates are constrained to their corresponding nominal masses [8] to improve the resolution of the measurement of the four-momentum of their
parent B candidate. The $\chi_c$ candidates are formed from $J/\psi$ and photon candidates. The photon is required to have an energy greater than 0.15 GeV and not to be part of $\pi^0$ candidates in the mass range $[0.125, 0.140]$ GeV/$c^2$.

Candidate B mesons are formed from $\chi_c$ and $K^{(*)}$ candidates. Two kinematic variables are used to further remove incorrectly reconstructed B candidates. The first is the difference $\Delta E = E_B - E_{\text{beam}}$ between the B-candidate energy and the beam energy in the Y(4S) rest frame. In the absence of experimental effects, reconstructed signal candidates have $\Delta E = 0$. The typical $\Delta E$ resolution is 20 MeV for channels with only charged tracks in the final state, and 25 MeV, with a low $\Delta E$ tail due to energy leakage in the calorimeter, for channels with a $\pi^0$. The second variable is the beam-energy-substituted mass $m_{\text{ES}} = (E^2_{\text{beam}}/c^4 - p^2_B/c^2)^{1/2}$, where $p_B$ is the momentum of the B candidate in the Y(4S) rest frame. The energy substituted mass $m_{\text{ES}}$ should peak at the B meson mass, 5.279 GeV/$c^2$. Typical resolution for $m_{\text{ES}}$ is 2.7 MeV/$c^2$. For the signal region, $\Delta E$ is required to be in the range $[-35, +20]$ MeV for channels involving a $\pi^0$, and within ±20 MeV otherwise. We require $m_{\text{ES}}$ to be in the range $[5.274, 5.284]$ GeV/$c^2$. If more than one B candidate is found in an event, the one having the smallest $|\Delta E|$ is retained.

The observation of $\chi_{c2}$ could be complicated by the presence of the prominent $\chi_{c1}$ peak. This is mitigated by measuring the spectrum in the variable $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$. The efficiencies obtained from fits to the mass difference distribution for exclusive MC samples, where one B decays to the final state under consideration and the other inclusively, are given in Table I. The $\chi_{c2}$ meson has a natural width of just 2 MeV [8] and is therefore fitted with a Gaussian to account for detector resolution. Since the $\chi_{c0}$ has a natural width of 10 MeV [8], comparable to the mass resolution ($\sigma = 10$ MeV/$c^2$), we fit the $\chi_{c0}$ peak with the convolution of Breit-Wigner and Gaussian shapes.

Studies of MC samples show that most of the background events in the $\chi_c K^*$ channels are due to nonresonant (NR) $B \to \chi_c(J/\psi\gamma)K\pi$ decays. After the NR events are removed from the MC background sample, the expected background with genuine $\chi_c \to J/\psi\gamma$ decays is the 0.2 ± 0.2 event for the $\chi_{c2}K^{0*}(K^+\pi^-)$ and $\chi_{c2}K^{+}(K^0\pi^0)$ modes, and 0.0 ± 0.2 for all other channels. We correct for the presence of NR decays with the following procedure. The $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ distribution for events in a nearby sideband ($1.1 < m_{K\pi} < 1.3$ GeV/$c^2$) is subtracted from the distribution for events in the signal region ($0.85 < m_{K\pi} < 0.94$ GeV/$c^2$), after scaling the sideband distribution by a factor $r = 0.26 ± 0.04$. The quantity $r$, obtained from the MC simulation, is the ratio of NR events under the peak to the number in the sideband. NR-subtracted distributions of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ are shown in Fig. 1. These plots show the presence of the factorization-allowed $\chi_{c1}$ but no significant signals for the factorization-suppressed $\chi_{c0}$ or $\chi_{c2}$. No $\chi_{c0}$ or $\chi_{c2}$ signal is observed in the sideband region.

The branching fractions are computed from $BF = N_S/(N_B \epsilon f)$, where $N_S$ is the number of signal events obtained from fitting the $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ distribution (Table II), $N_B$ is the number of produced $B \bar{B}$ events, $\epsilon$ is the selection efficiency (Table I), and $f$ is the product of secondary branching fractions of the $B$ daughters. The free parameters in the fits are the size of a constant background, the overall scale of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$, and the amplitudes of the resonant peaks. The fixed parameters are the $\chi_{c0}$ natural width, the $\chi_{c0} - \chi_{c1}$ and $\chi_{c2} - \chi_{c1}$ mass differences ($-95.4$ and $+45.7$ MeV/$c^2$, respectively) all taken from Ref. [8], and the mass resolution. The mass resolution, 10.2 ± 0.4 MeV/$c^2$, is measured with $\chi_{c1}$ data and is assumed to be the same for the three $\chi_c$ states. Performing such fits to an inclusive $Y(4S) \to B \bar{B}$ MC sample, we verify that the NR events are subtracted correctly, and that the proximity of the $\chi_{c1}$ does not induce any significant bias on the measurement of the nearby $\chi_{c2}$.

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<thead>
<tr>
<th>$\chi_{c2}$</th>
<th>$\chi_{c0}$</th>
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<tr>
<td>$K^{*0}(K^+\pi^-)$</td>
<td>0.071 ± 0.001</td>
</tr>
<tr>
<td>$K^{*0}(K^0\pi^0)$</td>
<td>0.031 ± 0.001</td>
</tr>
<tr>
<td>$K^0_S$</td>
<td>0.158 ± 0.001</td>
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<tr>
<td>$K^{*+}(K^+\pi^0)$</td>
<td>0.036 ± 0.001</td>
</tr>
<tr>
<td>$K^{*+}(K^0\pi^+$</td>
<td>0.065 ± 0.001</td>
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<tr>
<td>$K^+$</td>
<td>0.144 ± 0.001</td>
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FIG. 1. Distribution of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ for data, with NR subtraction for final states of the strange meson (a) $K^+\pi^-$, (b) $K^0_S\pi^0$, (c) $K^0_S$, (d) $K^{*+}\pi^0$, (e) $K^0\pi^+$, and (f) $K^+$. The fit is described in the text. The arrows on plot (f) show the expected positions of the $\chi_{c0}$ and $\chi_{c2}$ peaks.
Based on studies of $B \to J/\psi K^*$ decays [10], the NR $K \pi$ component appears to be in an $S$-wave state, with an unknown relative phase $\phi$ with respect to the main $K^*(892)$ $P$-wave peak. As no signal is found, the systematic uncertainty due to the unknown relative phase is estimated here with a MC-based method. The $K^- \pi^-$ invariant mass is fitted with an amplitude that is the sum of a nonrelativistic Breit-Wigner function and an amplitude with a constant phase and the square of which has a quadratic dependence on $m_{K\pi}$.

$$p(m_{K\pi}) = \left| \frac{a}{m_{K\pi} - m_{K^*} - i\Gamma/2} + b(m_{K\pi})e^{i\phi} \right|^2,$$

where $a$ and $b$ are real quantities and $m_{K^*} = 892$ MeV/$c^2$. The slow variation of the phase of the $S$ wave with $m_{K\pi}$ is neglected here. The free parameters in the fit are the 3 degrees of freedom of the quadratic dependence of $b$, the magnitude of the signal, and the relative phase $\phi$. As the sideband is dominated by the NR contribution, no attempt is made to subtract the few combinatorial events. The fact that the phase $\phi$ is unknown is dealt with by randomly generating samples of events distributed as above for each value of $\phi$, and applying NR subtraction. The number of events $N(\phi)$ thus measured is normalized to that obtained with the phase value $\phi_0$ obtained in the fit. The ratio $R = N(\phi)/N(\phi_0)$ shows a sinusoidal dependence. The average value is 1.44 with a deviation of ±35%, giving an rms relative uncertainty of ±20%, which we assume is systematic uncertainty (due to the interference with the NR component).

In the case of decays to the tensor $\chi_{c2}$, the efficiency depends on the intensity fractions to each of three polarization states. The efficiency is mainly sensitive to the value of the helicity angle $\theta_{K^*}$ of the $K^*$ decay, because small values of $\theta_{K^*}$ occur for low momentum pions. The selection efficiency therefore depends, to first order, on the polarization of the $K^*$ population, through the normalized differential decay rate:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{K^*}} = \frac{3}{4} \left[ (1 - \cos^2 \theta_{K^*}) + A_0(3\cos^2 \theta_{K^*} - 1) \right],$$

where $A_0$ is the fraction of longitudinal $K^*$ polarization.
TABLE V. Upper limits at 90% C.L. and measured branching fractions (in parentheses) in units of $10^{-4}$.

<table>
<thead>
<tr>
<th>$\chi_{e2}$</th>
<th>$\chi_{e0}$</th>
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<tbody>
<tr>
<td>$K^{*0}$</td>
<td>0.36 (0.14 $\pm$ 0.11 $\pm$ 0.14)</td>
</tr>
<tr>
<td>$K^{*+}$</td>
<td>0.12 ($-0.15 \pm 0.05 \pm 0.14$)</td>
</tr>
<tr>
<td>$K^+$</td>
<td>0.30 (0.09 $\pm$ 0.10 $\pm$ 0.11)</td>
</tr>
<tr>
<td>$K^0$</td>
<td>0.41 (0.21 $\pm$ 0.11 $\pm$ 0.13)</td>
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assumed to be unity. The related uncertainty is small [11] and is neglected here. A summary of the multiplicative contributions to the systematics can be found in Table IV. In addition to these multiplicative contributions, there is a small contribution from the uncertainty on $r$ for the NR background subtraction.

Combining the measurements of the $K^*$ submodes, and with the approximation that the multiplicative efficiencies for each $K^*$ submode are fully correlated, we obtain the branching fractions for the factorization-suppressed modes listed in Table V. As a cross-check, the results for the allowed $\chi_{e1}$ are found to be compatible with those of a recent analysis [12] optimized for that decay. We obtain upper bounds on the BFIs at 90% confidence level (C.L.) assuming Gaussian statistics for the statistical uncertainties and taking into account the systematic uncertainties. We have used a Bayesian method with uniform prior for positive BF values in the derivation of these limits. The upper limits obtained for decays to $\chi_{e0}$ are larger than for $\chi_{e2}$ due to the smaller $\chi_{e0}$ radiative BF. For $B^+ \rightarrow \chi_{e0}K^+$ they are compatible with the previous measurements [4,5].

$B \rightarrow \chi_{e(0,2)}K^{(*)}$ production requires nonfactorizable contributions. $B^+ \rightarrow \chi_{e0}K^+$ decays have been previously observed. Colangelo et al. [7] explain this with rescattering effects and predict a similar rate for $B \rightarrow \chi_{e2}K$. This is not observed. The upper limits obtained for decays to $\chi_{e2}$ are approximately 1 order of magnitude lower than the branching fractions of the observed $B^+ \rightarrow \chi_{e0}K^+$ decays.

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