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

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We search for the factorization-suppressed decays $B \to \chi_{c0} K^{(*)}$ and $B \to \chi_{c2} K^{(*)}$, with χ_{c0} and χ_{c2} decaying into $J/\psi\,\gamma$, using a sample of 124×10^6 $B\overline{B}$ events collected with the *BABAR* detector at the PEP-II storage ring of the Stanford Linear Accelerator Center. We find no significant signal and set upper bounds for the branching fractions.

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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, $B \to c\overline{c}K^{(*)}$ decays are allowed when the $c\overline{c}$ pair hadronizes to J/ψ, $\psi(2S)$ or χ_{c1}, but suppressed when the $c\overline{c}$ pair hadronizes to χ_{c0} or χ_{c2} [2]. Here, $K^{(*)}$ represents either K or K^*. In lowest-order Heavy Quark Effective Theory, there is no $J \geq 2$ current to create the tensor χ_{c2} from the vacuum. The decay rate to the scalar χ_{c0} is zero due to charge conjugation invariance [3].

Belle has recently observed $B^+ \to \chi_{c0}K^+$ decays with a branching fraction (BF) of $(6.0^{+2.1}_{-1.8} \pm 1.1) \times 10^{-4}$ [4] using χ_{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 $B^+ \to \chi_{c1}K^+$ and are surprisingly large given the expectation from factorization. Using the hadronic χ_{c0} decays, CLEO has obtained an upper limit on $B^0 \to \chi_{c0}K^0$ of 5.0×10^{-4} [6]. Non-factorizable contributions to $B^+ \to \chi_{c0}K^+$ decays due to rescattering of intermediate charm states have been considered theoretically [7], and similar branching fractions are predicted for decays to χ_{c0} and χ_{c2}. No predictions are available for B decays to $\chi_{c(0,2)}K^*$, 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 $B \to \chi_{c(0,2)}K^{(*)}$ 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 $B \to \chi_{cJ}K^{(*)}$, $J = 0, 2$, using the radiative decays $\chi_{cJ} \to J/\psi\,\gamma$, with branching fractions of $(1.18 \pm 0.14)\%$, $(20.2 \pm 1.7)\%$, respectively [8]. Since the radiative branching fraction for the χ_{c0} decay (including subsequent J/ψ decay to $\ell^+\ell^-$) is much smaller than the corresponding $\pi^+\pi^-$ or K^+K^- branching fractions, the search for the $B^+ \to \chi_{c0}K^+$ decay is less sensitive than previous searches, but it is free from the interference with the non-resonant 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 $112\,\mathrm{fb}^{-1}$ of data taken at the $\Upsilon(4S)$ 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 (EMC) detects photons and electrons. The calorimeter is surrounded by a solenoidal magnet providing a 1.5-T field. The flux return is instrumented with resistive plate chambers used for muon and neutral-hadron identification.

The channels considered here are $B \to \chi_c K^{(*)}$ with $\chi_c \to J/\psi\,\gamma$ and $J/\psi \to \ell^+\ell^-$, where ℓ is e or μ; K is K^+ or K^0_S ($\to \pi^+\pi^-$); $K^{*0} \to K^+\pi^-$ or $K^0_S\pi^0$; $K^{*+} \to K^+\pi^0$ or $K^0_S\pi^+$; and $\pi^0 \to \gamma\gamma$. Charge-conjugate modes are included implicitly throughout this paper. Event selection is optimized by maximizing $\epsilon/\sqrt{B}$, where ϵ is the signal efficiency after all selection requirements and B the number of background events, estimated with $\Upsilon(4S) \to B\overline{B}$ and $e^+e^- \to q\overline{q}$ Monte Carlo (MC) samples.

Candidate J/ψ 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/ψ mesons not originating from χ_c decays.

We form K^0_S candidates from oppositely-charged tracks originating from a common vertex with invariant mass in the range [487, 510] MeV/c^2. The K^0_S 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^0_S 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 π^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 $350\,\mathrm{MeV}/c$. K^* candidates are formed from $K\pi$ combinations with an invariant mass in the range [0.85, 0.94] GeV/c^2.

The J/ψ, K^0_S, and π^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 χ_c candidates are formed from J/ψ and photon candidates. The photon is required to have an energy greater than $0.15\,\mathrm{GeV}$ and not to be part of π^0 candidates in the mass range [0.125, 0.140] GeV/c^2.

Candidate B mesons are formed from χ_c and $K^{(*)}$ candidates. Two kinematic variables are used to further remove incorrectly reconstructed B candidates. The first is the difference $\Delta E \equiv E^*_B - E^*_{beam}$ between the B-candidate energy and the beam energy in the $\Upsilon(4S)$ rest frame. In the absence of experimental effects, reconstructed signal candidates have $\Delta E = 0$. The typical ΔE resolution is 20 MeV for channels with only charged tracks in the final state, and 25 MeV, with a low ΔE tail due to energy leakage in the calorimeter, for channels with a π^0. The second variable is the beam-energy-substituted mass $m_{\mathrm{ES}} \equiv (E^{*2}_{beam} - p^{*2}_B)^{1/2}$, where p^*_B is the momentum of the B-candidate in the $\Upsilon(4S)$ rest frame. The energy substituted mass m_{ES} should peak at the B meson mass, $5.279\,\mathrm{GeV}/c^2$. Typical resolution for ΔE is 2.7 MeV/c^2. For the signal region, ΔE is required to be in the range $[-35, +20]\,\mathrm{MeV}$ for channels involving a π^0, and within $\pm 20\,\mathrm{MeV}$ otherwise. We require m_{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 χ_{c2} could be complicated by the presence of the prominent χ_{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 χ_{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 χ_{c0} has a natural width of 10 MeV [8], comparable to the mass resolution ($\sigma \approx 10\,\mathrm{MeV}/c^2$), we fit the χ_{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 non-resonant (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 a genuine $\chi_c \to J/\psi\gamma$ decays is 0.2 ± 0.2 event for the $\chi_{c2}K^{*0}(K^+\pi^-)$ and $\chi_{c2}K^{*+}(K^+\pi^0)$ 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 ($1.1 < m_{K\pi} < 1.3\,\mathrm{GeV}/c^2$) is subtracted from the distribution for events in the signal region ($0.85 < m_{K\pi} < 0.94\,\mathrm{GeV}/c^2$), after scaling the sideband distribution by a factor $r = 0.26 \pm 0.04$. The quantity r, obtained from 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 χ_{c1} but no significant signals for the factorization-suppressed χ_{c0} or χ_{c2}. No χ_{c0} or χ_{c2} signal is observed in the sideband region.

TABLE I: Efficiencies from fits of exclusive MC distributions of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$, with statistical uncertainty.

	χ_{c2}	χ_{c0}
K^{*0} $(K^+\pi^-)$	0.071 ± 0.001	0.066 ± 0.001
K^{*0} $(K^0_S\pi^0)$	0.031 ± 0.001	0.020 ± 0.001
K^0_S	0.158 ± 0.001	0.126 ± 0.001
K^{*+} $(K^+\pi^0)$	0.036 ± 0.001	0.031 ± 0.001
K^{*+} $(K^0_S\pi^+)$	0.065 ± 0.001	0.062 ± 0.001
K^+	0.144 ± 0.001	0.117 ± 0.002

TABLE II: Event yields with statistical uncertainties from the fits of Fig. 1.

	χ_{c2}	χ_{c0}
K^{*0} $(K^+\pi^-)$	2.0 ± 1.6	1.7 ± 2.1
K^{*0} $(K^0_S\pi^0)$	-1.6 ± 4.3	0.5 ± 0.3
K^0_S	3.4 ± 1.8	3.9 ± 3.8
K^{*+} $(K^+\pi^0)$	-0.5 ± 0.2	1.1 ± 2.2
K^{*+} $(K^0_S\pi^+)$	-1.9 ± 1.2	5.9 ± 3.7
K^+	3.7 ± 4.4	8.8 ± 6.6

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 $B\overline{B}$ events, ϵ 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 χ_{c0} natural width, the χ_{c0}–χ_{c1} and χ_{c2}–χ_{c1} mass differences (-95.4 and $+45.7\,\mathrm{MeV}/c^2$, respectively) all taken from Ref. [8], and the mass resolution. The mass resolution, $10.2 \pm 0.4\,\mathrm{MeV}/c^2$, is measured with χ_{c1} data and is assumed to be the same for the three χ_c states. Performing such fits to an inclusive $\Upsilon(4S) \to B\overline{B}$ MC sample, we verify that the NR events are subtracted correctly, and that the proximity of the χ_{c1} does not induce any significant bias on the measurement of the nearby χ_{c2}.

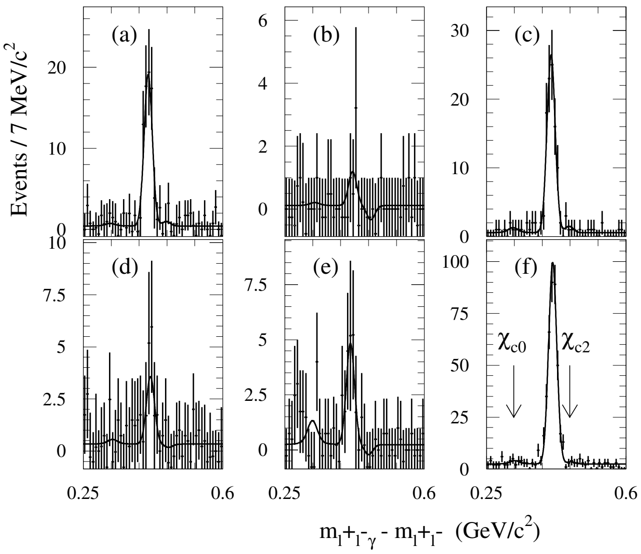

FIG. 1: Distribution of $m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-}$ for data, with NR subtraction for final states of the strange meson (a) $K^+\pi^-$, (b) $K^0_S\pi^0$, (c) K^0_S, (d) $K^+\pi^0$, (e) $K^0_S\pi^+$, (f) K^+. The fit is described in the text. The arrows on plot (f) show the expected positions of the χ_{c0} and χ_{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 ϕ 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 non-relativistic Breit-Wigner and an amplitude with a constant phase and the square of which has a quadratic dependence on $m_{K\pi}$.

$$p(m_{K\pi}) = \left| \frac{a}{m_{K^*} - m_{K\pi} - i\Gamma/2} + b(m_{K\pi})e^{i\phi} \right|^2 , \quad (1)$$

where a and b are real quantities and $m_{K^*} = 892\,\mathrm{MeV}/c^2$. 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 three degrees of freedom of the quadratic dependence of b, the magnitude of the signal, and the relative phase ϕ. As the sideband is dominated by the NR contribution, no attempt is made to subtract the few combinatorial events. The fact that the phase ϕ is unknown is dealt with by randomly generating samples of events distributed as above for each value of ϕ, and applying NR subtraction. The number of events $N(\phi)$ thus measured is normalized to that obtained with the phase value ϕ_0 obtained in the fit. The ratio $R = N(\phi)/N(\phi_0)$ shows a sinusoidal dependance. The average value is 1.44 with a deviation of ±35%, giving an RMS relative uncertainty of ±20%, which we will assume as systematic uncertainty (due to the interference with the NR component).

In the case of decays to the tensor χ_{c2}, the efficiency depends on the intensity fractions to each of three polarization states. The efficiency is mainly sensitive to the value of the K^* helicity angle θ_{K^*}, because small values of θ_{K^*} occur for low momentum pions. The selection efficiency therefore depends, to first order, on the polarization of the K^* population, through the angular distribution:

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

where A_0 is the fraction of longitudinal K^* polarization. The average efficiency is

$$\langle\varepsilon\rangle = \int \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{K^*}}\varepsilon(\theta_{K^*})d\cos\theta_{K^*} = a + A_0 b, \quad (3)$$

where $a = \frac{3}{4}\int(1-\cos^2\theta_{K^*})\varepsilon(\theta_{K^*})\sin\theta_{K^*}d\theta_{K^*}$, and $b = \frac{3}{4}\int(3\cos^2\theta_{K^*} - 1)\varepsilon(\theta_{K^*})\sin\theta_{K^*}d\theta_{K^*}$, where $\varepsilon(\theta_{K^*})$ is obtained from MC. The values of a and b are shown in Table III.

When no signal is observed, as is the case here, the polarization is unknown. We assume an unpolarized decay and we estimate the efficiency as $(a + 0.5b) \pm (|b|/\sqrt{12})$. The branching fraction measurements reported here are affected by the systematic uncertainties described in what follows. The relative uncertainty on the number of $B\overline{B}$ events is 1.1%. The secondary branching fractions and their uncertainty are taken from Ref. [8]. Other estimated uncertainties are: tracking efficiency, 1.3% per track added linearly; K^0_S reconstruction, 2.5%; selection of the γ from the χ_c decays, 2.5%; π^0 selection, 5.0%; PID efficiency, 3.0%. For each mass peak and for ΔE, the uncertainty of the central value and of the width of the peaks are measured with the χ_{c1} channels. These quantities are used to estimate the efficiency uncertainty from this source. The ratio of B^0 to B^+ production in $\Upsilon(4S)$ decays is 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.

TABLE III: Coefficients for the calculation of amplitude-dependent average efficiency for the $\chi_{c2}K^*$ channels (%).

	a	b	Efficiency
K^{*0} $(K^+\pi^-)$	8.68	-1.40	7.98± 0.40
K^{*0} $(K^0_S\pi^0)$	4.25	-1.66	3.43± 0.48
K^{*+} $(K^+\pi^0)$	5.05	-1.79	4.16± 0.52
K^{*+} $(K^0_S\pi^+)$	7.83	-1.84	6.92± 0.53

Combining the measurements of the K^* sub-modes, and with the approximation that the multiplicative efficiencies for each K^* sub-mode are fully correlated,

TABLE IV: Summary of the multiplicative systematic uncertainties in percent. The first eight rows are in common to decays to χ_{c0} and χ_{c2}.

	$K^+\pi^-$	$K^0_S\pi^0$	$K^+\pi^0$	$K^0_S\pi^+$	K^+	K^0_S
Number of B's	1.1	1.1	1.1	1.1	1.1	1.1
Tracking	5.2	2.6	3.9	3.9	3.9	2.6
K^0_S	–	2.5	–	2.5	–	2.5
Neutrals	2.5	7.5	7.5	2.5	2.5	2.5
PID	3.0	3.0	3.0	3.0	3.0	3.0
Sample selection	7.7	13.1	11.6	8.2	6.5	6.3
MC statistics	1.4	2.9	1.7	1.8	1.3	1.3
S-wave Phase	20.0	20.0	20.0	20.0	–	–
χ_{c0} second. BF	11.9	11.9	11.9	11.9	11.9	11.9
Total for χ_{c0}	25.4	28.3	27.6	25.5	14.8	14.6
χ_{c2} second. BF	8.5	8.5	8.5	8.5	8.5	8.5
Polarization	5.1	14.0	12.4	7.7	–	–
Total for χ_{c2}	24.5	30.5	29.1	25.3	12.2	12.0

we obtain the branching fractions for the factorization-suppressed modes listed in Table V. As a cross check, the results for the allowed χ_{c1} are found to be compatible with those of a recent analysis [12] optimized for that decay. We obtain upper bounds on the BFs 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 χ_{c0} are larger than for χ_{c2} due to the smaller χ_{c0} radiative BF. For $B^+ \rightarrow \chi_{c0}K^+$ they are compatible with the previous measurements [4, 5].

$B \rightarrow \chi_{c(0,2)}K^{(*)}$ production requires non-factorizable contributions. $B^+ \rightarrow \chi_{c0}K^+$ decays have been previously observed. Colangelo *et al.* [7] explain this with rescattering effects and predict a similar rate for $B \rightarrow \chi_{c2}K$. This is not observed. The upper limits obtained for decays to χ_{c2} are approximately one order of magnitude lower than the branching fractions of the observed $B^+ \rightarrow \chi_{c0}K^+$ decays. Furthermore, we find no evidence for the decays $B \rightarrow \chi_{c(0,2)}K^*$.

TABLE V: Upper limits at 90% C.L. and measured branching fractions (in pararentheses) in units of 10^{-4}.

	χ_{c2}		χ_{c0}	
K^{*0}	0.36	(0.14 ± 0.11 ± 0.14)	7.7	(3.8 ± 2.6 ± 1.5)
K^{*+}	0.12	(-0.15 ± 0.05 ± 0.14)	28.6	(13.5 ± 9.6 ± 5.3)
K^+	0.30	(0.09 ± 0.10 ± 0.11)	8.9	(4.4 ± 3.3 ± 0.7)
K^0	0.41	(0.21 ± 0.11 ± 0.13)	12.4	(5.3 ± 5.0 ± 0.8)

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