Evidence for X(3872)--> psi (2S) gamma in B±-->X(3872)K± Decays and a Study of B-->cc-bar gamma K

Evidence for $X(3872) \to \psi(2S)\gamma$ in $B^{\pm} \to X(3872)K^{\pm}$ Decays and a Study of $B \to c\bar{c}\gamma K$

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In a search for $B \to c\bar{c}\gamma K$ decays with the *BABAR* detector, where $c\bar{c}$ includes J/ψ and $\psi(2S)$, and K includes $K^{\pm}$, K^0_S, and $K^*(892)$, we find evidence for $X(3872) \to J/\psi\gamma$ and $X(3872) \to \psi(2S)\gamma$ with 3.6σ and 3.5σ significance, respectively. We measure the product of branching fractions $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \times \mathcal{B}(X(3872) \to J/\psi\gamma) = [2.8 \pm 0.8(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-6}$ and $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma) = [9.5 \pm 2.7(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-6}$.

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The $X(3872)$ state discovered by the Belle Collaboration in the decay $B^{\pm} \to K^{\pm}X(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$ [1] is now well established [2]. *BABAR* has seen evidence for the decay $X(3872) \to J/\psi\gamma$, which implies positive C-parity [3]. A variety of theoretical interpretations [4] exist for this state, including conventional charmonium interpretations [5] and exotic QCD proposals such as a $\bar{D}^0D^{*0}$ molecule [6]. While $\bar{D}^0D^{*0}$ molecular proposals can accommodate decays to $J/\psi\gamma$, the branching fraction for decays to $\psi(2S)\gamma$ is expected to be very small [7]. These models allow for the possibility of an admixture of a $\bar{D}^0D^{*0}$ bound state with, for example, a $c\bar{c}$ meson. Because the $\chi_{c1}(2P)$ state potentially decays to $\psi(2S)\gamma$ at a rate many times higher than to $J/\psi\gamma$, the decay $X(3872) \to \psi(2S)\gamma$ could be enhanced due to $c\bar{c}$-$\bar{D}^0D^{*0}$ mixing.

We present a study of the decay $B \to XK$, where the notation X represents any state decaying radiatively to $J/\psi\gamma$ or $\psi(2S)\gamma$ [the $\chi_{c1,2}$ and $X(3872)$ states in particular], and K encompasses $K^{\pm}$, K^0_S, $K^{*\pm}(892)$, and $K^{*0}(892)$. We consider J/ψ mesons decaying to e^+e^- or $\mu^+\mu^-$, and $\psi(2S)$ decaying to e^+e^-, $\mu^+\mu^-$, or $J/\psi\pi^+\pi^-$. Kaons are required to decay to final states consisting of charged particles: $K^0_S \to \pi^+\pi^-$, $K^{*\pm} \to K^0_S(\pi^+\pi^-)\pi^{\pm}$, and $K^{*0} \to K^{\pm}\pi^{\mp}$.

The data sample for this analysis consists of (465 ± 5) million $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- collider at SLAC. This represents 424 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance. The *BABAR* detector is described in detail elsewhere [8]. The event selection, determined independently from the data, is based on Monte Carlo (MC) simulated events with the aim of maximizing significance.

The J/ψ candidates are formed using pairs of leptons whose invariant mass is in the range $(2.96, 3.15)$ GeV$/c^2$ for electrons (including bremsstrahlung photons) and $(3.06, 3.13)$ GeV$/c^2$ for muons. For $\psi(2S) \to \ell^+\ell^-$, the candidate invariant masses are required to be in the range $(3.61, 3.73)$ GeV$/c^2$ for electrons or $(3.65, 3.72)$ GeV$/c^2$ for muons. The $\psi(2S) \to J/\psi\pi^+\pi^-$ candidates are composed of J/ψ candidates decaying as described but with a tighter mass requirement of $(3.01, 3.15)$ GeV$/c^2$ for the e^+e^- decay mode. To form a $\psi(2S)$ candidate, the J/ψ candidate is mass constrained to the nominal PDG value [9] and combined with a pair of oppositely charged tracks requiring $(0.4, 0.6)$ GeV$/c^2$ and $(3.68, 3.69)$ GeV$/c^2$ for the dipion and $\psi(2S)$ invariant masses, respectively. All four final decay particles are constrained to the same decay vertex. Electrons are identified by a likelihood-based selector with $>92\%$ efficiency and negligible fake rate. Muons are selected by a neural net process with $>85\%$ efficiency and a π (K) fake rate of $<6\%$ ($<10\%$). Pions are drawn from the list of all charged tracks in the event.

We reconstruct $X \to c\bar{c}\gamma$ candidates from a mass-constrained J/ψ ($\psi(2S)$) candidate combined with a photon with an energy greater than 30(100) MeV. Additional selection criteria are applied to the shape of the lateral distribution $(0.001 < \text{LAT} < 0.5)$ [10] and azimuthal asymmetry (as measured by the Zernike moment $A_{42} < 0.1$) [11] of the photon-shower energy. For $X \to J/\psi\gamma$, the radiative γ candidate is rejected if, when combined with any other γ from the event, it has an invariant mass consistent with the π^0 mass, $124 < m_{\gamma\gamma} < 146$ MeV$/c^2$.

The K^0_S candidates are required to be within ± 17 MeV$/c^2$ of the nominal K^0_S mass [9], and the significance of the distance of the reconstructed decay vertex from the primary vertex must be greater than 3.7 standard deviations (σ). The excited kaons are required to have an invariant mass within the range $0.7 < m(K^*) < 1.1$ GeV$/c^2$. For K^0_S, $K^{*\pm}$, and K^{*0} candidates associated with $X \to \psi(2S)\gamma$, additional requirements are placed on the χ^2 vertex probability of the kaon, $P(\chi^2) > 0.001$, 0.02, and 0.002, respectively. Kaons are chosen by a likelihood-based selector with an efficiency of $\sim$95% and misidentification rates of $\sim$5%, $\sim$4%, and $<10\%$ for π, μ, and p, respectively, over the momentum range in this analysis.

We form the final B candidate from an X candidate and a kaon constrained to originate from the same vertex. To identify B candidates, we use two kinematic variables, m_B and m_{miss}. The unconstrained mass of the reconstructed B candidate is $m_B = \sqrt{E_B^2/c^4 - p_B^2/c^2}$, where E_B and p_B are obtained by summing the energies and momenta of the particles in the candidate B meson. The missing mass is defined as $m_{\text{miss}} = \sqrt{(p_{e^+e^-} - \hat{p}_B)^2/c^2}$, where $p_{e^+e^-}$ is the four-momentum of the beam e^+e^- system and $\hat{p}_B$ is the four-momentum of the B candidate after applying a B mass constraint. For $X \to J/\psi[\psi(2S)]\gamma$ events, we require m_B to be within $^{+30}_{-36}(\pm 20)$ MeV$/c^2$ of the nominal B mass [9]. Our B candidate selection is further refined by imposing criteria on the χ^2 probability for the B vertex: for all $X \to J/\psi\gamma$ modes, $P(\chi^2) > 0.0001$, and for $X \to \psi(2S)\gamma$ modes, $P(\chi^2) > 0.01$, 0.002, and 0.05 for the $K^{\pm}$, K^0_S, and K^* modes, respectively. The ratio of the second and zeroth Fox-Wolfram moments ($R_2 < 0.45$) [12] is used to separate isotropic B events from continuum background events. Once a B candidate has been established, it and its daughter decays are refit with the B mass constrained to the known value [9].

We perform a one(two)-dimensional unbinned extended maximum-likelihood (UML) fit to $m_{\rm miss}$ (and m_{K^*}, if applicable), and use the ${}_s$Plot formalism [13] to project our signal events into m_X, the invariant mass of the X candidate. This is a background-subtraction technique by weighting each event based on how signal- or background-like it is. The ${}_s$Plot displays the number of $B \to XK$ signal-like events as a function of m_X. We extract the signal yield for a given decay mode by fitting this resultant m_X distribution with shapes for signal and background determined from MC simulation.

The signal event probability density functions (PDFs) are determined from MC-simulated $B \to \chi_{c1}K$ and $B \to X(3872)K$ events. Only reconstructed events exactly matching the generated decay chain particles are used to parameterize the signal PDFs. The PDF shapes for $B \to \chi_{c2}K$ are the same as for χ_{c1}, with the below-noted exception of the m_X distribution. The $m_{\rm miss}$ distribution is modeled with a Crystal Ball function [14], m_X with a single Gaussian for the χ_{c2} decay modes and narrower core Gaussian plus a second wider Gaussian sharing the same mean for all other signal modes, and m_{K^*} with the convolution of a Breit-Wigner and a Gaussian.

The background PDFs are determined from fits to generic B^+B^-, $B^0\bar{B}^0$, $q\bar{q}$, and $\tau^+\tau^-$ MC samples, and are dominated by events from $B\bar{B}$ decays that include a J/ψ or $\psi(2S)$ in their decay chain. For the $B^\pm \to XK^\pm$ and $B^0 \to XK^0_S$ decay modes, the background in $m_{\rm miss}$ consists of two parts: a nonpeaking combinatoric component modeled with an ARGUS function [15], and a peaking component that shares the Crystal Ball parameterization used for signal events. These backgrounds are modeled as linear in m_X. The K^* decay modes have three background components: events that peak in $m_{\rm miss}$ but are flat in m_{K^*} ("nonresonant") and vice versa ("K^* combinatoric"), and those that do not peak in either distribution ("combinatoric"). The peaking $m_{\rm miss}$ and m_{K^*} distributions use the same parameterization and values found by fitting to the signal MC sample. The nonpeaking $m_{\rm miss}$ distributions are fit with an ARGUS function, while the nonpeaking m_{K^*} distribution is modeled with a linear function. Both combinatoric background types are flat in m_X, while the nonresonant backgrounds (typically $B \to XK\pi$) have a flat and peaking component in m_X. However, because none of these background events are signal-like in both $m_{\rm miss}$ and m_{K^*}, they are not present in the ${}_s$Plot projection in m_X.

To account for potential differences between data and MC calculations, the values for the $m_{\rm miss}$ ARGUS and m_X

TABLE I. Summary of the analysis results. N_S is the bias-corrected number of signal events extracted from the m_X ${}_s$Plot, σ is the total significance of the signal yield N_S measured in standard deviations (statistical and systematic uncertainties combined in quadrature) from the null result, ϵ is the total efficiency for the decay mode, and derived $\mathcal{B}$ is the measurement (with 90% confidence level upper limit [16]) of $\mathcal{B}(B \to \chi_{c1,2}K)$ or $\mathcal{B}(B \to X(3872)K) \times \mathcal{B}(X \to c\bar{c}\gamma)$. Uncertainties are statistical and systematic, respectively.

Decay	N_S	σ	ϵ(%)	Derived $\mathcal{B}$
χ_{c1}				$\times 10^{-4}$
$\chi_{c1}K^\pm$	$1018 \pm 34 \pm 14$	28	11.0	$4.5 \pm 0.1 \pm 0.3$
$\chi_{c1}K^0$	$242 \pm 16 \pm 5$	14	8.7	$4.2 \pm 0.3 \pm 0.3$
$\chi_{c1}K^{*\pm}$	$71 \pm 13 \pm 8$	4.7	5.7	$2.6 \pm 0.5 \pm 0.4$
$\chi_{c1}K^{*0}$	$255 \pm 25 \pm 11$	9.5	7.9	$2.5 \pm 0.2 \pm 0.2$
χ_{c2}				$\times 10^{-5}$
$\chi_{c2}K^\pm$	$14.0 \pm 7.9 \pm 1.1$	1.8	12.3	$1.0 \pm 0.6 \pm 0.1 (<1.8)$
$\chi_{c2}K^0$	$6.1 \pm 3.9 \pm 1.1$	1.5	11.1	$1.5 \pm 0.9 \pm 0.3 (<2.8)$
$\chi_{c2}K^{*\pm}$	$1.2 \pm 4.7 \pm 6.1$	0.2	4.2	$1.1 \pm 4.3 \pm 5.5 (<12)$
$\chi_{c2}K^{*0}$	$38.8 \pm 10.5 \pm 1.1$	3.7	8.3	$6.6 \pm 1.8 \pm 0.5$
$X(3872)(J/\psi\gamma)$				$\times 10^{-6}$
$XK^\pm$	$23.0 \pm 6.4 \pm 0.6$	3.6	14.5	$2.8 \pm 0.8 \pm 0.1$
XK^0	$5.3 \pm 3.6 \pm 0.2$	1.5	11.0	$2.6 \pm 1.8 \pm 0.2 (<4.9)$
$XK^{*\pm}$	$0.6 \pm 2.3 \pm 0.1$	0.3	6.9	$0.7 \pm 2.6 \pm 0.1 (<4.8)$
XK^{*0}	$2.8 \pm 5.2 \pm 0.4$	0.5	10.4	$0.7 \pm 1.4 \pm 0.1 (<2.8)$
$X(3872)(\psi(2S)\gamma)$				$\times 10^{-6}$
$XK^\pm$	$25.4 \pm 7.3 \pm 0.7$	3.5	10.4	$9.5 \pm 2.7 \pm 0.6$
XK^0	$8.0 \pm 3.9 \pm 0.5$	2.0	8.4	$11.4 \pm 5.5 \pm 1.0 (<19)$
$XK^{*\pm}$	$1.9 \pm 2.9 \pm 2.9$	0.5	5.0	$6.4 \pm 9.8 \pm 9.6 (<28)$
XK^{*0}	$-1.4 \pm 3.3 \pm 0.3$	$\cdots$	6.7	$-1.3 \pm 3.1 \pm 0.3 (<4.4)$

linear parameters for the background events are left as free parameters in the final fit to data. We also allow the height of the m_X Gaussian peaks to float, which we use to derive the number of signal events.

The effectiveness of the signal extraction method is validated on fully simulated MC events for $\chi_{c1,2}$ and $X(3872)$ signal events, with random samples generated from the MC background distribution. Successful performance of the fit is verified on simulated datasets assuming the number of signal and background events from the known branching fractions and efficiencies. We apply small corrections (<5%) to account for bias in the results of the MC fit validation.

We determine the efficiency from the fraction of the events generated in MC simulation that survive the analysis selection criteria and are returned by the fitting procedure. We calculate the branching fraction for each decay mode using $\mathcal{B}(B \to XK) = N_S/(N_{B\bar{B}} \times \epsilon \times f)$ where N_S is the bias-corrected number of signal events from the fit to the m_X ${}_s$Plot, $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs in the data set, ϵ is the total signal extraction efficiency, and f represents all secondary branching fractions. The fit results, efficiencies, and derived branching fractions are summarized in Table I.

For most of the $B \to X(3872)K$ decay channels, the largest source of systematic uncertainty affecting the signal yield comes from the uncertainty in the true $X(3872)$ mass and width (~2% for the $K^{\pm}$ modes). In the case of the $K^{\pm}$ and K_S^0 decay modes for $X(3872) \to \psi(2S)\gamma$, an alternate parametrization of the m_X shape was considered for background events, as indicated by the MC simulation. A correction equal to half the difference between the results of the two background model choices, with a systematic error equal to this amount, is applied to the final result. This is the largest yield-related systematic uncertainty for the $X(3872)(\psi(2S)\gamma)K^{\pm}$ mode (~2%). For $B \to \chi_{c1,2}K$, uncertainty in the fit bias, PDF parameters, and MC-data differences for the mean value m_X for signal events all contribute in varying though roughly equal amounts.

Regarding systematic uncertainties related to the branching fraction calculations, one of the main contributors is the total uncertainty associated with the identification of all particle types (~4%). The uncertainty in secondary branching fractions, beyond the control of this analysis, is the dominant systematic uncertainty for $\mathcal{B}(B \to \chi_{c1}K)$ and $\mathcal{B}(B^0 \to \chi_{c2}K^{*0})$ (~6%). Effects from tracking, photon corrections and B counting are also considered, but are all less than 2%.

Figure 1 shows the fit to m_X in the mass range $3.411 < m_X < 3.611$ GeV$/c^2$. We observe all of the expected $B \to \chi_{c1}K$ decay modes, in good agreement with previous measurements. We find 3.7σ evidence for $B^0 \to \chi_{c2}K^{*0}$, and set upper limits for the remaining $B \to \chi_{c2}K$ decays.

Fits to m_X in the range $3.772 < m_X < 3.972$ GeV$/c^2$ are shown in Fig. 2 for decays to $J/\psi\gamma$. We confirm evidence for the decay $X(3872) \to J/\psi\gamma$ in $B^{\pm} \to X(3872)K^{\pm}$, measuring $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \times \mathcal{B}(X(3872) \to J/\psi\gamma) = [2.8 \pm 0.8(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-6}$ with a significance of 3.6σ. This value is in good agreement with the previous *BABAR* result [3], which it supersedes, and represents the most precise measurement of this branching

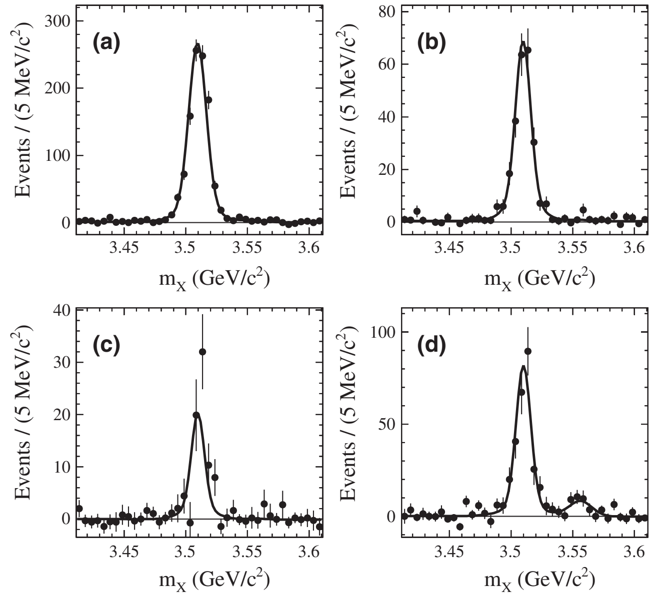

FIG. 1. ${}_s$Plot of the number of signal events versus m_X for (a) $B^{\pm} \to \chi_{c1,2}K^{\pm}$, (b) $B^0 \to \chi_{c1,2}K_S^0$, (c) $B^{\pm} \to \chi_{c1,2}K^{*\pm}$, and (d) $B^0 \to \chi_{c1,2}K^{*0}$. The solid curve is the fit to the data.

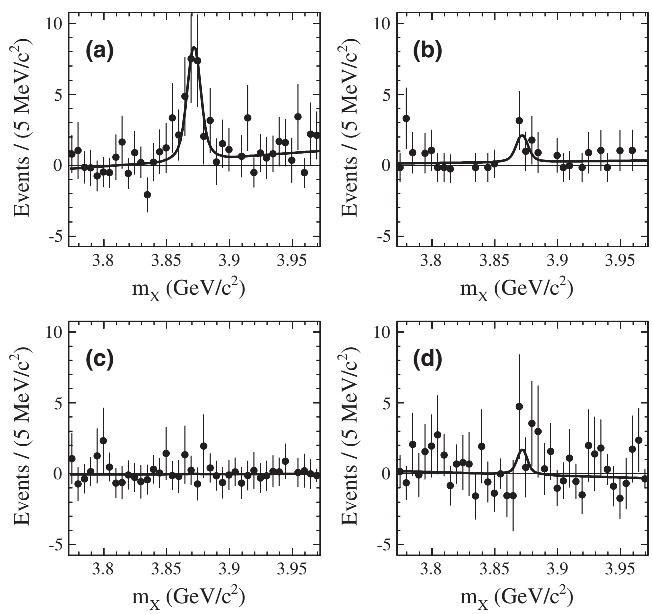

FIG. 2. ${}_s$Plot of the number of extracted signal events versus m_X for (a) $B^{\pm} \to X(3872)K^{\pm}$, (b) $B^0 \to X(3872)K_S^0$, (c) $B^{\pm} \to X(3872)K^{*\pm}$, and (d) $B^0 \to X(3872)K^{*0}$, where $X(3872) \to J/\psi\gamma$. The solid curve is the fit to the data.

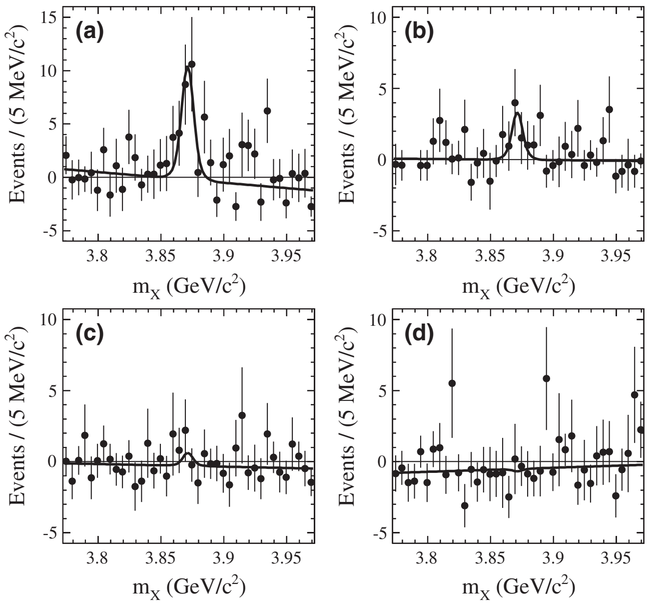

FIG. 3. $_s$Plot of the number of extracted signal events versus m_X for (a) $B^\pm \to X(3872)K^\pm$, (b) $B^0 \to X(3872)K_S^0$, (c) $B^\pm \to X(3872)K^{*\pm}$, and (d) $B^0 \to X(3872)K^{*0}$, where $X(3872) \to \psi(2S)\gamma$. The solid curve is the fit to the data.

fraction to date. We find no significant signal in the other decay modes.

Figure 3 shows the fit to the m_X distribution for $X \to \psi(2S)\gamma$ in the range $3.772 < m_X < 3.972$ GeV/c^2. In our search for $X(3872) \to \psi(2S)\gamma$ in $B^\pm \to X(3872)K^\pm$, we find the first evidence for this decay with a significance of 3.5σ. We derive $\mathcal{B}(B^\pm \to X(3872)K^\pm) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma) = [9.5 \pm 2.7(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-6}$. We find no significant signals in the other decay modes.

To search for other new resonances, the m_X invariant mass window is extended up to the kinematic limit. Even after combining all decay modes together, there are no indications of any further signals above the prominent $X(3872)$ peak.

In summary, we present first evidence for the decay $X(3872) \to \psi(2S)\gamma$, and updated measurements of the $X(3872) \to J/\psi\gamma$ and $B \to \chi_{c1,2}K$ decays. We find evidence for the factorization-suppressed [17] decay $B^0 \to \chi_{c2}K^{*0}$, but see no evidence for other $\chi_{c2}K$ decays. Taking the statistical and systematic errors in quadrature, we find a ratio of $\frac{\mathcal{B}(X(3872)\to\psi(2S)\gamma)}{\mathcal{B}(X(3872)\to J/\psi\gamma)} = 3.4 \pm 1.4$. This relatively large branching fraction for $X(3872) \to \psi(2S)\gamma$ is generally inconsistent with a purely $\bar{D}^0 D^{*0}$ molecular interpretation of the $X(3872)$, and possibly indicates mixing with a significant $c\bar{c}$ component.

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