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Search for $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\gamma$

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In a study of $B^+ \to J/\psi\gamma K^+$ decays, we find evidence for the radiative decay $X(3872) \to J/\psi\gamma$ with a statistical significance of 3.4σ. We measure the product of branching fractions $\mathcal{B}(B^+ \to X(3872)K^+) \cdot \mathcal{B}(X(3872) \to J/\psi\gamma) = (3.3 \pm 1.0 \pm 0.3) \times 10^{-6}$, where the uncertainties are statistical and systematic, respectively. We also measure the branching fraction $\mathcal{B}(B^+ \to \chi_{c1}K^+) = (4.9 \pm 0.2 \pm 0.4) \times 10^{-4}$. These results are obtained from (287 ± 3) million $B\bar{B}$ decays collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II *B* Factory at SLAC.

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The $X(3872)$ state was discovered by the Belle Collaboration [1] in the decay $B^+ \to X(3872)K^+$ [2]. This signal was confirmed by the *BABAR* Collaboration [3], as well as the CDF and D0 Collaborations [4]. Interpreting this new state has been challenging. Its narrow width, mass near the $\bar{D}^0 D^{*0}$ threshold, and small branching fraction for the radiative decay $X(3872) \to \chi_{c1}\gamma$ have made it difficult to identify the $X(3872)$ with any of the predicted charmonium states [5]. Alternate proposals have been made, including a $\bar{D}^0 D^{*0}$ molecule [6], or a diquark-antidiquark state [7]. CDF recently measured the dipion mass spectrum in $X(3872) \to J/\psi\pi^+\pi^-$ decays [8]. Their results favor the decay $X(3872) \to J/\psi\rho$, implying $C = +$. Evidence for the radiative $X(3872) \to J/\psi\gamma$ decay in $B^+ \to X(3872)K^+$ would determine the C-parity of the $X(3872)$ state to be positive, limiting the conventional charmonium assignment options while remaining consistent with $\bar{D}^0 D^{*0}$ molecule model predictions.

A number of other new states have recently been found. The Belle Collaboration has claimed the discovery of a broad resonance in B decays, referred to here as the $Y(3940)$ state [9]. The nature of this state is unknown, and there is no reason to yet preclude $B^+ \to Y(3940)K^+$, $Y(3940) \to J/\psi\gamma$ as a possible decay channel. Belle has also identified a possible χ'_{c2} charmonium candidate in two-photon production, referred to here as the $Z(3930)$ state [10]. This state could be produced in B decays, and if the tentative χ'_{c2} charmonium assignment holds true, it should decay radiatively to $J/\psi\gamma$ (albeit at a rate predicted [11] to be on the order of 0.1%).

We study the decay chain $B^+ \to c\bar{c}K^+$, where $c\bar{c}$ decays radiatively to $J/\psi\gamma$, and the J/ψ subsequently decays to a lepton pair. The notation $c\bar{c}$ represents conventional charmonium, such as the triplet $\chi_{cJ}(1P)$ states, or any state with positive C-parity for which the $J/\psi\gamma$ decay is not forbidden.

The data sample for this analysis consists of (287 ± 3) million $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- collider. This represents 260 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance. The *BABAR* detector is described in detail elsewhere [12]. The innermost component of the detector is a double-sided five-layer silicon vertex tracker for precise reconstruction of B-decay vertices. A 40-layer drift chamber measures charged-particle momentum. A ring-imaging detector of internally reflected Cherenkov radiation is used for particle identification. Energy deposited by electrons and photons is measured by a CsI(Tl) crystal electromagnetic calorimeter (EMC). These detector subsystems are surrounded by a solenoid producing a 1.5-T magnetic field. The flux return for the magnet is instrumented with a muon detection system composed of resistive plate chambers. For the most recent 51 fb^{-1} of data, a portion of the muon system has been replaced by limited streamer tubes [13].

A $J/\psi \to \ell^+\ell^-$ candidate is reconstructed by combining a pair of oppositely charged muon or electron candidates having an invariant mass compatible with the nominal J/ψ mass. An attempt is made to recover energy loss due to bremsstrahlung by searching for photons near electron candidates. Candidates for J/ψ are then combined with a candidate kaon and a photon to form a $B^+ \to J/\psi\gamma K^+$ candidate.

The $J/\psi \to e^+e^-$ candidates are formed with electrons (and bremsstrahlung photons) with $2.950 < m(e^+e^-(\gamma)) < 3.170\ \text{GeV}/c^2$. Candidates for $J/\psi \to \mu^+\mu^-$ require muons with $3.060 < m(\mu^+\mu^-) < 3.135\ \text{GeV}/c^2$. The $c\bar{c}$ candidate is reconstructed from the mass-constrained J/ψ and a photon with E_γ greater than 30 MeV. Additional selection criteria are applied to the shape of the lateral distribution (LAT) [14] and azimuthal asymmetry (measured by the Zernike moment, A_{42}) [15] of the photon-shower energy deposited in the EMC. The radiative γ candidate is rejected if, when combined with any other γ from the event, the invariant mass is consistent with the π^0 mass (see Table I). The ratio of the second and zeroth Fox-Wolfram moments (R_2) [16] is

TABLE I. Summary of acceptance criteria for candidate events.

Region
$2.950 < m_{e^+e^-}(\gamma) < 3.170\ \text{GeV}/c^2$
$3.060 < m_{\mu^+\mu^-} < 3.135\ \text{GeV}/c^2$
$R_2 < 0.35$
$\text{LAT} < 0.5$
$A_{42} < 0.1$
Reject $122 < m_{\pi^0 \to \gamma\gamma} < 145\ \text{MeV}/c^2$

used to separate isotropic B^+ events from typically anisotropic continuum background events. The mass of the $c\bar{c}$ candidates, $m_{c\bar{c}}$, is calculated by constraining the B^+ candidate to the nominal B^+ mass.

To identify B candidates, we use two kinematic variables, m_B and $m_{\rm miss}$. The unconstrained mass of the reconstructed B candidate $m_B = \sqrt{E_B^2/c^4 - p_B^2}$, where E_B and p_B are obtained by summing the energies and momentum of the particles in the candidate B meson, respectively. The missing mass is defined through $m_{\rm miss} = \sqrt{(p_{e^+e^-} - \hat{p}_B)^2}$, 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. These variables are uncorrelated by construction, and are advantageous for analyzing B decays in which a particle in the final state has poorly measured energy. Events with a correctly reconstructed B^+ decay should have values equal to the nominal B^+ mass for both kinematic variables.

To best separate signal from background, the signal selection criteria are chosen based on Monte Carlo (MC) samples by maximizing the figure of merit $n_S/(\alpha/2 + \sqrt{n_B})$ [17] where n_S and n_B are numbers of signal and background events, respectively, and α represents the minimum level of significance desired. For this analysis, $\alpha = 3$ is chosen. The optimization is performed by varying the selection values for $m_{e^+e^-}(\gamma)$, $m_{\mu^+\mu^-}$, R_2, photon LAT, photon A_{42}, and the photon π^0 veto, while requiring m_B and $m_{\rm miss}$ to be within 100 MeV$/c^2$ of the nominal B^+ meson mass. The optimized criteria used in this analysis are summarized in Table I.

We extract the signal with an unbinned two-dimensional extended maximum-likelihood (ML) fit to the kinematic variables m_B and $m_{\rm miss}$ in 10 MeV$/c^2$ bins of $m_{c\bar{c}}$. Fits failing to converge or lacking statistics are combined with adjacent $m_{c\bar{c}}$ bins to ensure fit success. The probability density functions (PDFs) for signal extraction are the product of independent fits in m_B and $m_{\rm miss}$, defined separately for signal and background events.

The signal PDFs are determined from Monte Carlo simulation of $B^+ \to \chi_{c1}K^+$ and $B^+ \to X(3872)K^+$ decays. The m_B and $m_{\rm miss}$ distributions of $B^+ \to c\bar{c}K^+$ signal events are both modeled by a functional form similar to a Gaussian with asymmetric tails, $f(x) = \exp[-(x-m)^2/(2\sigma_\pm^2 + \alpha_\pm(x-m)^2)]$, where the $\pm$ subscript indicates different parameter values on either side of the central peak. The signal PDFs for these two $c\bar{c}$ modes are found to be equivalent to one another within statistical uncertainty.

The background consists of two parts, a combinatoric component with a flat distribution in the kinematic variables m_B and $m_{\rm miss}$, and a component that peaks in $m_{\rm miss}$ composed of B decays similar to our decay mode. The peaking background events are mostly from $B^+ \to J/\psi K^+\pi^0$, $\pi^0 \to \gamma\gamma$ and $B^+ \to J/\psi K^{*+}$, $K^{*+} \to K^+\pi^0$, $\pi^0 \to \gamma\gamma$ decays. These events are incorrectly reconstructed as the desired final state if one of the photons from the π^0 decay is undetected. This background does not peak in the other kinematic variable m_B, nor in $m_{c\bar{c}}$. The only doubly peaking background may arise from $B^+ \to J\psi K^{*+}$, $K^{*+} \to K^+\gamma$. These events can peak in both m_B and $m_{\rm miss}$, but the product of branching fractions for this decay mode is 1.3×10^{-6}. Because this decay rate is small and does not peak in the $m_{c\bar{c}}$ region we are interested in, the contribution from this background is negligible. The simulation also indicates that the combinatorial background is almost entirely due to B decays.

The background PDFs are fitted to events from generic B^+B^-, $B^0\bar{B}^0$, $q\bar{q}$ ($q = u, d, s, c$), and $\tau^+\tau^-$ MC samples. In m_B, all background events are modeled by the tail of a wide Gaussian function. The $m_{\rm miss}$ distribution of background events is parametrized by the ARGUS background shape [18] for the combinatoric component, while the peaking component is characterized by a Gaussian function.

The maximum-likelihood fit returns the number of $B^+ \to c\bar{c}K^+$ signal events, $N_{\rm sig}$, in each 10 MeV$/c^2$ $m_{c\bar{c}}$ bin. The number of signal events is found by fitting to the $N_{\rm sig}$ versus $m_{c\bar{c}}$ results with functions representing the $c\bar{c}$ mass distribution of each signal mode. Based on Monte Carlo simulation of the $\chi_{cJ=0,1,2}$ and $X(3872)$ [19] decays, the $m_{c\bar{c}}$ shape for each of these signals is individually parametrized with a double Gaussian distribution. In the fit to the ML results, the Gaussian means, widths, and ratios of the areas are fixed to the values determined from the MC simulation, with the heights of the peaks permitted to float. As $N_{\rm sig}$ can also include nonsignal events peaking in both m_B and $m_{\rm miss}$, a first order polynomial in $N_{\rm sig}$ versus $m_{c\bar{c}}$ was included to account for the level of the doubly peaking backgrounds. The number of $c\bar{c}$ events is calculated from the area of the fitted Gaussians above this background.

The effectiveness of the signal extraction method is validated on Monte Carlo samples for $\chi_{c0,1}$ and $X(3872)$. It is found that the proximity of the large χ_{c1} signal peak introduces a significant negative bias in the measurement of a χ_{c2} signal with this method. Therefore we do not quote results for the χ_{c2} mode. Successful performance of the $X(3872)$ extraction is verified on Monte Carlo generated samples for numbers of events similar to the measured value, as well as for the case of a null result.

The efficiency is determined by calculating the fraction of the events generated in Monte Carlo simulation that survived the analysis selection criteria from Table I and are returned by the fitting procedure. Standard *BABAR* corrections are applied to account for particle identification and tracking differences found between simulation and data. These corrections are at the level of a few percent. The resulting efficiencies are $(16.8 \pm 0.2)\%$ for the

TABLE II. Summary of systematic uncertainties. The uncertainty due to secondary branching fractions (BFs) does not apply to the product of branching fraction results.

Source	χ_{c0}(%)	χ_{c1}(%)	$X(3872)$(%)
B counting	1.1	1.1	1.1
Secondary BFs	8.5	5.4	1.0
MC statistics	16.5	3.2	8.7
$m_{c\bar{c}}$ shape	3.1	1.3	1.5
Particle ID	2.0	2.0	2.0
Tracking	3.6	3.6	3.6
Photons	1.8	1.8	1.8
Fit technique	1.7	1.7	1.7
$X(3872)$ mass/width	···	···	2.0
Total	19.5	8.1	10.3

$X(3872)$ mode, $(13.3 \pm 0.2)\%$ for χ_{c0}, and $(13.5 \pm 0.3)\%$ for χ_{c1}, where the errors are statistical.

Systematic uncertainties on the branching fractions are reported in Table II. Sources include uncertainty in the number of $B\bar{B}$ pairs, uncertainty in the secondary branching fractions for $\chi_{c0,1} \to J/\psi\gamma$ and $J/\psi \to \ell^+\ell^-$, PDF parametrization uncertainty due to MC statistics, uncertainty in the $m_{c\bar{c}}$ parametrization, particle identification, tracking and photon corrections, effects due to fit technique (such as choice of $m_{c\bar{c}}$ bin width and fit starting point), and uncertainty in the true $X(3872)$ mass and width. The uncertainties due to MC statistics, $m_{c\bar{c}}$ and $X(3872)$ mass were evaluated by varying the individual parameter values by 1σ from their measured values and finding their effect on the signal yield. The $X(3872)$ state was assumed to have a mass of 3.872 ± 0.001 GeV$/c^2$. For χ_{c1}, the fit technique uncertainty includes a component accounting for the change in yield if the χ_{c2} signal is required to be physical (non-negative). The choice of parametrization of the doubly peaking backgrounds in $N_{\rm sig}$ versus $m_{c\bar{c}}$ was varied from a first order polynomial to a constant term, but no impact on the signal yield or significance was found. The largest source of uncertainty (aside from secondary branching fractions which are beyond the control of this analysis) is due to the variation in signal yield with the choice of PDF parameter values. In the case of the $X(3872)$ signal, the total uncertainty is dominated by statistical rather than systematic errors.

Figure 1 shows the fit to $m_{c\bar{c}}$ in the mass range $3.311 < m_{c\bar{c}} < 3.711$ GeV$/c^2$. We extract 27.9 ± 11.7 χ_{c0} events and 807.2 ± 33.3 χ_{c1} events. Using our signal extraction efficiencies, we calculate the product of branching fractions $\mathcal{B}(B^+ \to \chi_{c1}K^+) \cdot \mathcal{B}(\chi_{c1} \to J/\psi\gamma) = (1.76 \pm 0.07 \pm 0.12) \times 10^{-4}$ and $\mathcal{B}(B^+ \to \chi_{c0}K^+) \cdot \mathcal{B}(\chi_{c0} \to J/\psi\gamma) = (6.1 \pm 2.6 \pm 1.1) \times 10^{-6}$, where the first error is statistical and the second is systematic. Taking the branching fractions for $\chi_{c0,1} \to J/\psi\gamma$ from [20], we calculate $\mathcal{B}(B^+ \to \chi_{c1}K^+) = (4.9 \pm 0.2 \pm 0.4) \times 10^{-4}$, and $\mathcal{B}(B^+ \to \chi_{c0}K^+) = (4.7 \pm 2.0 \pm 0.9) \times 10^{-4}$, corresponding to the 90% confidence level upper limit of $\mathcal{B}(B^+ \to \chi_{c0}K^+) < 7.5 \times 10^{-4}$. The statistical significance of the χ_{c0} signal is 2.4σ. These branching fraction results are consistent with the current world average [20] and, in the case of $B^+ \to \chi_{c1}K^+$, more precise.

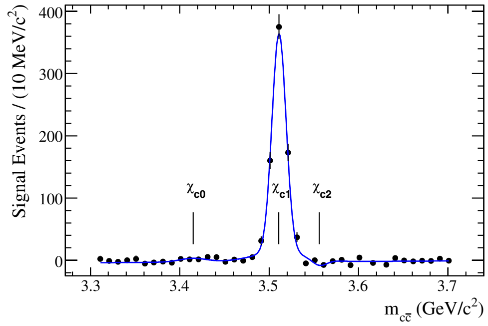

FIG. 1 (color online). Number of extracted signal events versus $m_{c\bar{c}}$ for χ_{cJ}. The solid curve is the fit to the data. The χ^2 per degree of freedom for this fit is 48.7/34.

We extract the number of $X(3872)$ signal events in the mass range $3.672 < m_{c\bar{c}} < 4.072$ GeV$/c^2$ and find 19.2 ± 5.7 events (Fig. 2). We derive the product of branching fractions $\mathcal{B}(B \to X(3872)K^+) \cdot \mathcal{B}(X(3872) \to J/\psi\gamma) = (3.3 \pm 1.0 \pm 0.3) \times 10^{-6}$. The statistical significance of this signal, taken to be the square root of the difference in χ^2 values between the fit in Fig. 2 and a similar fit assuming zero signal events, is 3.4σ.

Additional fits are performed to search for the $Y(3940)$ and $Z(3930)$ states by adding a resonance in the appropriate mass region. The measurement of the $Y(3940)$ state from [9] finds a mass of 3943 ± 17 MeV$/c^2$ and width of 87 ± 34 MeV$/c^2$, while the $Z(3930)$ state is found to have a mass of 3929 ± 5 MeV$/c^2$ and width of 29 ± 10 MeV$/c^2$ [10], where the statistical and systematic uncertainties have been combined in quadrature. We model the mass resolution for the decays of each of these states to $J/\psi\gamma$ by a Gaussian function in $m_{c\bar{c}}$ with the mean and sigma fixed to the Belle measurements. Because the masses and photon energies are similar, we assume the same efficiency for these modes as for the $X(3872)$ state.

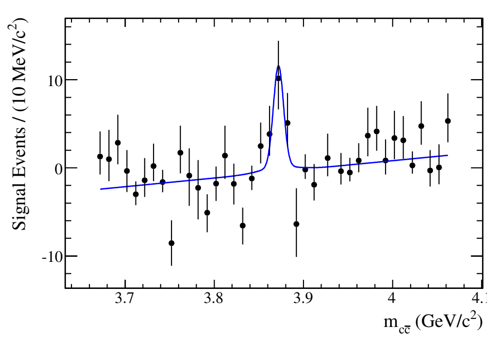

FIG. 2 (color online). Number of extracted signal events versus $m_{c\bar{c}}$ for the $X(3872)$ region. The solid curve is the fit to the data. The χ^2 per degree of freedom for this fit is 46.3/36.

We find -16 ± 34 events and -5.4 ± 8.3 events for the $Y(3940)$ and $Z(3930)$ states, respectively. We define an upper limit on the product of branching fractions by assuming a Gaussian distribution for the number of signal events and its uncertainty, and integrate over the physically allowed region from 0% to 90% of the total area around the mean. Systematic errors are estimated from the contributions listed for the $X(3872)$ in Table II. Uncertainties on the $Y(3940)$ and $Z(3930)$ masses and widths dominate entirely. The total systematic uncertainty on the product of branching fractions is 101% for the $Y(3940)$ and 22% for the $Z(3930)$. To account for the width uncertainty, it was varied by 1σ from the measured value and the largest resulting upper limit retained. Using these basic assumptions, we calculate $\mathcal{B}(B \to Y(3940)K^+) \cdot \mathcal{B}(Y(3940) \to J/\psi\gamma) < 1.4 \times 10^{-5}$ and $\mathcal{B}(B \to Z(3930)K^+) \cdot \mathcal{B}(Z(3930) \to J/\psi\gamma) < 2.5 \times 10^{-6}$ at the 90% confidence level.

In summary, we measure the branching fraction $\mathcal{B}(B^+ \to \chi_{c1}K^+) = (4.9 \pm 0.2 \pm 0.4) \times 10^{-4}$ and determine a 90% confidence level upper limit of $\mathcal{B}(B^+ \to \chi_{c0}K^+) < 7.5 \times 10^{-4}$. We find the product of branching fractions $\mathcal{B}(B \to X(3872)K^+) \cdot \mathcal{B}(X(3872) \to J/\psi\gamma) = (3.3 \pm 1.0 \pm 0.3) \times 10^{-6}$, with a statistical significance of 3.4σ. This provides evidence of the radiative decay $X(3872) \to J/\psi\gamma$ and of charge parity $C = +$ for the $X(3872)$ state. We search for radiative decays of the $Y(3940)$ and $Z(3930)$ states to $J/\psi\gamma$ in the $B^+ \to c\bar{c}K^+$ channel, and find no evidence for such modes.

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