Measurements of the Absolute Branching Fractions of $B^{\pm} \to K^{\pm} X_{c\bar{c}}$

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We study the two-body decays of $B^{\pm}$ mesons to $K^{\pm}$ and a charmonium state $X_{c\bar{c}}$ in a sample of 210.5 fb^{-1} of data from the *BABAR* experiment. We perform measurements of absolute branching fractions $\mathcal{B}(B^{\pm} \to K^{\pm} X_{c\bar{c}})$ using a missing mass technique, and report several new or improved results. In particular, the upper limit $\mathcal{B}(B^{\pm} \to K^{\pm} X(3872)) < 3.2 \times 10^{-4}$ at 90% C.L. and the inferred lower limit $\mathcal{B}(X(3872) \to J/\psi \pi^{+} \pi^{-}) > 4.2\%$ will help in understanding the nature of the recently discovered $X(3872)$.

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Several exclusive decays of B mesons of the form $B^{\pm} \to K^{\pm} X_{c\bar{c}}$ (where $X_{c\bar{c}}$ is one of the charmonium states η_c, J/ψ, χ_{c0}, χ_{c1}, η_c', ψ', ψ'') have been observed by reconstructing the charmonium state from its decay to some known final state, f [1,2]. In principle, such B decays provide a direct probe of charmonium properties since the phase space is large for all known states and all should be produced roughly equally, in the absence of a strong selection rule [3]. However, with this technique only the product of the two branching fractions $\mathcal{B}(B^{\pm} \to K^{\pm} X_{c\bar{c}}) \times \mathcal{B}(X_{c\bar{c}} \to f)$ is measured, thereby reducing the precision of $\mathcal{B}(B^{\pm} \to K^{\pm} X_{c\bar{c}})$ when the daughter branching fraction is poorly known.

We describe here a complementary approach, based on the measurement of the kaon momentum spectrum in the B center-of-mass frame, where two-body decays can be identified by their characteristic monochromatic line, allowing an absolute determination of $\mathcal{B}(B^{\pm} \to K^{\pm} X_{c\bar{c}})$. Knowledge of the B center-of-mass system is obtained by exclusive reconstruction of the other B meson from a $\Upsilon(4S)$ decay. In addition to obtaining new information on known charmonium states, this method is used to search for the $X(3872)$ state, recently observed in $B^{\pm} \to K^{\pm} X(3872)$ decays by Belle [4] and *BABAR* [5], in the subsequent decay $X(3872) \to J/\psi \pi^{+} \pi^{-}$. The same method allows a search for charged partners of the $X(3872)$ in B^0 decays, independent of the $X(3872)^{\pm}$ decay mode. The nature of $X(3872)$ resonance is still unclear; different interpretations [6] have been proposed but more experimental data will be needed to discriminate between them.

For this analysis we use a data sample of 210.5 fb^{-1} integrated luminosity, corresponding to 231.8×10^6 $B\bar{B}$ pairs. The data have been collected with the *BABAR* detector at the SLAC PEP-II asymmetric-energy collider, where 9 GeV electrons and 3.1 GeV positrons collide at a center-of-mass energy 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. A detailed description of the *BABAR* detector can be found in [7]. Charged tracks are reconstructed with a 5 layer silicon vertex tracker (SVT) and a 40 layer drift chamber (DCH), located in a 1.5 T magnetic field generated by a superconducting solenoid. The energy of photons and electrons is measured with an electromagnetic calorimeter made up of CsI(Tl) crystals. Charged hadron identification is done with ionization measurements in the SVT and DCH and with an internally reflecting ring imaging Cherenkov detector. The instrumented flux return of the solenoid is used to identify muons.

The analysis is performed on a sample of events where a B meson is fully reconstructed (B_{recon}). For these events, the momentum of the other B (B_{signal}) can be calculated from the momentum of B_{recon} and the beam parameters. We select events with a $K^{\pm}$ not used for the reconstruction of B_{recon} and calculate its momentum (p_K) in the B_{signal} center-of-mass system.

B_{recon} mesons are reconstructed in their decays to exclusive $D^{(*)}H$ final states, where H is one of several combinations of $\pi^{\pm}$, $K^{\pm}$, π^0, and K_S^0 hadrons; a detailed description of the method can be found in [8].

The number of $B^{\pm}$ events in the data is determined with a fit to the distribution of the beam energy substituted mass $m_{\text{ES}} = \sqrt{E_{\text{CM}}^2/4 - p_B^2}$, where E_{CM} is the total center-of-mass energy, determined from the beam parameters, and p_B is the measured momentum of B_{recon} in the center-of-mass frame. The fit function is the sum of a Crystal Ball function [9] describing the signal and an ARGUS function [10] for each background component ($e^+e^- \to q\bar{q}$ where q is u, d, s, or c or misreconstructed Bs), the relative weights of which are obtained from a Monte Carlo simulation (MC), while the total normalization factor is determined from the data. A total of $378\,580 \pm 1110$ events with a fully reconstructed $B^{\pm}$ is obtained.

Fifteen variables related to the B_{recon} decay characteristics, its production kinematics, the topology of the full event, and the angular correlation between B_{recon} and the rest of the event are used in a neural network (NN1) to reduce the large background, mainly due to non-B events. The network has 80% signal efficiency while rejecting 90% of the background. The m_{ES} distribution after this selection is shown in Fig. 1. Only events with $5.275 < m_{\text{ES}} < 5.285\ \text{GeV}/c^2$ are used in the analysis.

We now consider only tracks not associated with B_{recon}. Most $K^{\pm}$ produced in $B^{\pm}$ decays originate from D mesons and their spectrum, although broad, peaks at low p_K. In the $B^{\pm}$ rest frame, these $K^{\pm}$ are embedded in a "minijet" of D decay products, while signal $K^{\pm}$ recoil against a massive (3–4 GeV/c^2) state and therefore tend to be more isolated. A second neural network (NN2) rejects background from secondary $K^{\pm}$ by using 15 input variables describing the energy and track multiplicities measured in the $K^{\pm}$ hemisphere, the sphericity of the recoil system, and the angular

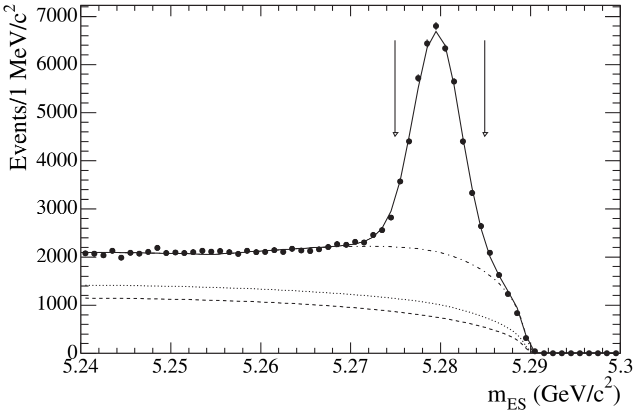

FIG. 1. The m_{ES} distribution of all B_{recon} after the NN1 selection. The solid line represents a fit described in the text; cumulative background contributions from $e^+e^- \to q\bar{q}$ where q is u, d, s, or c (dashed line), B^0 (dotted line), $B^\pm$ (dash-dotted line) events are shown. The arrows indicate the cuts used in the analysis (see text).

correlations between the $K^\pm$ and the recoil system. These variables have been chosen to be independent of the particular decay topology of the recoil system. Since the topology of the event changes with the recoil mass, we have considered separately two recoil mass regions in the training of this neural network: the "high-mass" region, corresponding to $1.0 < p_K < 1.5$ GeV/c and the "low-mass" region, for $1.5 < p_K < 2.0$ GeV/c. The signal training sample is $B^\pm \to K^\pm X_{c\bar{c}}$ MC simulation while the background sample consists of simulated $K^\pm$ from D meson decays in the same momentum range. The chosen cuts on the NN2 outputs correspond to 85% signal efficiency; the background rejection factor varies between 2.5 in the $X(3872)$ and ψ' region and 1.5 in the J/ψ region. The selection criteria are optimized for MC signal significance with the high-mass region blinded.

The kaon momentum distribution shows a series of peaks due to the two-body decays $B^\pm \to K^\pm X_{c\bar{c}}$ corresponding to the different $X_{c\bar{c}}$ masses, superimposed on a smooth spectrum due to $K^\pm$ coming from multibody $B^\pm$ decays, or non-$B^\pm$ background. The mass of the $X_{c\bar{c}}$ state (m_X) can be calculated directly from p_K using $m_X = \sqrt{m_B^2 + m_K^2 - 2E_K m_B}$, where m_B and m_K are the $B^\pm$ and $K^\pm$ masses and E_K is the $K^\pm$ energy. The resonance width Γ_X can be obtained from the Breit-Wigner width of the peak in the p_K spectrum Γ_K, obtained after deconvolution with the momentum resolution function, using $\Gamma_X = \Gamma_K \beta_K m_B / m_X$, where $\beta_K = p_K / E_K$.

We determine the number of $B^\pm \to K^\pm X_{c\bar{c}}$ events (N_X) from a fit to the p_K distribution. The branching fraction for the decay channel is calculated as:

$$\mathcal{B}(B^\pm \to K^\pm X_{c\bar{c}}) = \frac{N_X}{\epsilon_X N_B},$$

where ϵ_X is the efficiency determined from the MC simulation and N_B the number of $B^\pm$ mesons in the sample. An alternative method, which we use to improve the branching fraction measurement in the case of η_c, is to normalize to the channel $B^\pm \to K^\pm J/\psi$, which is well measured in the literature [11], according to:

$$\mathcal{B}(B^\pm \to K^\pm X_{c\bar{c}}) = \frac{N_X}{N_{J/\psi}} \frac{\epsilon_{J/\psi}}{\epsilon_X} \mathcal{B}(B^\pm \to K^\pm J/\psi).$$

In this relative measurement, the systematic errors that are common to both resonances cancel in the ratio. The two methods are combined to extract $\mathcal{B}(B^\pm \to K^\pm \eta_c)$, taking into account the correlations between them.

We fit the p_K spectrum using an unbinned maximum likelihood method. The background is well modeled by a third degree polynomial and each signal is a Breit-Wigner function folded with a resolution function. The masses and widths of the η_c and η_c' mesons are left free; all others are fixed to values from Ref. [11]. The resolution function has two parts: a Gaussian with σ varying from 6 MeV/c at $p_K \simeq 1.1$ GeV/c to 12 MeV/c at $p_K \simeq 1.7$ GeV/c describes the 72.5% of the signal where B_{recon} is correctly reconstructed; if B_{recon} is incorrect, but has m_{ES} within our range, the p_K resolution is a bifurcated Gaussian with $\sigma =$ 78 and 52 MeV/c on the left- and right-hand side of the peak, respectively.

The spectrum in the low-mass region is expected to exhibit two peaks, at $p_K = 1.683$ GeV/c corresponding to the J/ψ, and at $p_K = 1.754$ GeV/c for the η_c meson. These two peaks are clearly seen in Fig. 2(a); both have a significance of $\sim 7\sigma$. The number of events under each peak obtained from the fit is $N(J/\psi) = 259 \pm 41$ and $N(\eta_c) = 273 \pm 43$.

The spectrum in the high-mass region is fitted with a background and seven signal functions, corresponding to the following states: ψ', χ_{c0}, χ_{c1}, χ_{c2}, ψ'', η_c', and $X(3872)$. The resulting fit is shown in Fig. 2(b), with the yields given in Table I. The h_c charmonium state lies near the χ_{c1}, and it is difficult to distinguish the peaks from these two decays. A fit including the h_c yields a number of h_c events consistent with zero, and a fit performed with free χ_{c1} mass and width gives values consistent with a narrow χ_{c1}; therefore, we have no evidence for h_c production.

Several sources of systematic error affecting these measurements have been evaluated. The relative errors on absolute measurements are the same for all states; many of these cancel partially in relative measurements, and all are summarized in Table II. "B counting" refers to uncertainties in the fit parametrization used to determine the number of fully reconstructed $B^\pm_{\mathrm{recon}}$. It is one of the largest errors in absolute measurements, and cancels in ratios. The mass scale is verified to a precision of 1.5 MeV/c in p_K by floating the masses of the well-measured J/ψ, χ_{c1}, and ψ' peaks; we assign a systematic error corresponding to this shift. We also consider variations in the background and signal model parametrizations, which partially cancel in the case of ratios. Errors in the $K^\pm$ track reconstruction and

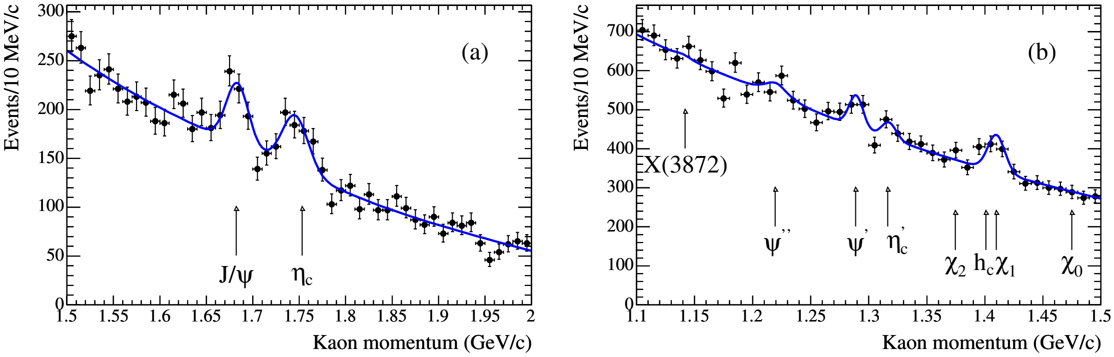

FIG. 2 (color online). Kaon momentum spectrum for the (a) low-mass and (b) high-mass regions. The lines represent the fit described in the text. Arrows show the expected positions of known charmonium states.

identification efficiency are evaluated by comparing data and MC control samples. The systematic error in the NN1 and NN2 selections is evaluated by comparing efficiencies and distributions in data and MC, and studying efficiency variation with p_K. We verified that the NN2 selection is not dependent on visible energy or multiplicity of the recoil part of the B meson decay. Adding in quadrature, the total relative error on an absolute measurement is 9.0%. The total is reduced to 3.3% for the relative measurement of J/ψ and η_c, and to 5.9% for states in the high-mass region relative to J/ψ. For the extraction of relative branching fractions, an additional 4% error, labeled (ext) in the following, comes from the present uncertainty of $\mathcal{B}(B^\pm \to K^\pm J/\psi) = (10.0 \pm 0.4) \times 10^{-4}$ [11].

In the high-mass region, clear signals are found for χ_{c1} and ψ' (with significance 6.0 and 3.2σ, respectively), an excess of events is present for η_c' and ψ'' [12], while no signal is found for χ_{c0}, χ_{c2}, and $X(3872)$. The branching fractions and upper limits are summarized in Table I.

TABLE I. Event yields and absolute branching fractions $\mathcal{B}(B^\pm \to K^\pm X_{c\bar{c}})$ from the fits to the p_K spectrum. The first error is statistical, the second systematic, and $\mathcal{B}$ upper limits are given at 90% C.L., taking into account the 9.0% systematic error. The last column shows the signal statistical significance σ, derived from the fit likelihood assuming 0 signal events $L(0)$: $\sigma = \sqrt{-2\log L(0)}$. For the η_c, both results for absolute and relative measurement, and their combination, are reported (see text).

Particle	Yield	$\mathcal{B}(10^{-4})$	σ
η_c	273 ± 43	8.4 ± 1.3 ± 0.8	7.3
η_c relative		10.6 ± 2.3 ± 0.4 ± 0.4	
η_c combined		8.7 ± 1.5	
J/ψ	259 ± 41	8.1 ± 1.3 ± 0.7	6.9
χ_{c0}	9 ± 21	<1.8	···
χ_{c1}	227 ± 40	8.0 ± 1.4 ± 0.7	6.0
χ_{c2}	0 ± 36	<2.0	···
η_c'	98 ± 52	3.4 ± 1.8 ± 0.3	1.8
ψ'	139 ± 44	4.9 ± 1.6 ± 0.4	3.2
ψ''	99 ± 69	3.5 ± 2.5 ± 0.3	1.4
$X(3872)$	15 ± 39	<3.2	···

In the low-mass region, our J/ψ measurement is consistent with the world average. From the η_c and J/ψ yields and the reference branching fraction we can derive the result with the relative measurement method $\mathcal{B}(B^\pm \to K^\pm \eta_c)_{\rm rel} = (10.6 \pm 2.3({\rm stat}) \pm 0.4({\rm sys}) \pm 0.4({\rm ext})) \times 10^{-4}$. We combine this result with the absolute measurement of Table I, taking the correlated errors into account, to obtain $\mathcal{B}(B^\pm \to K^\pm \eta_c) = (8.7 \pm 1.5) \times 10^{-4}$.

We obtain from our fits the η_c and η_c' masses and widths and find $m_{\eta_c} = 2982 \pm 5$ MeV$/c^2$, $\Gamma_{\eta_c} < 43$ MeV, and $m_{\eta_c'} = 3639 \pm 7$ MeV$/c^2$, $\Gamma_{\eta_c'} < 23$ MeV, where the width limits are both at 90% C.L.

Taking $\mathcal{B}(B^\pm \to K^\pm X(3872)) < 3.2 \times 10^{-4}$, and using an average of the Belle [4] and *BABAR* [5] measurements of $\mathcal{B}(B^\pm \to K^\pm X(3872)) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ we set a lower limit $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) > 4.2\%$ at 90% C.L. This branching fraction, for which there are not yet any predictions, is sensitive to the distribution of charm quarks inside the $X(3872)$. A search for charged partners of the $X(3872)$ is performed by examining $K^\pm$ recoiling from a sample of 245.6 k reconstructed B^0 decays. No signal is seen and we find $\mathcal{B}(B^0 \to K^\pm X(3872)^\mp) < 5 \times 10^{-4}$ at 90% C.L.

TABLE II. Summary of systematic errors in percent for absolute and the J/ψ:η_c relative measurement.

Source	Absolute (%)	J/ψ:η_c (%)
B counting	4.5	0
Mass scale	1	1
Background model	3.5	1.7
Resolution model	2.3	1.0
$K^\pm$ reconstruction	1.3	0
$K^\pm$ identification	5	1
B mass selection	0.5	0
NN1 selection	2.2	2.0
NN2 selection	3.2	1.0
Total	9.0	3.3

We combine our $\mathcal{B}(B^{\pm} \rightarrow K^{\pm}\eta_c)$ with a previous *BABAR* measurement of $\mathcal{B}(B^{\pm} \rightarrow K^{\pm}\eta_c) \times \mathcal{B}(\eta_c \rightarrow K\bar{K}\pi)$ [13] to obtain $\mathcal{B}(\eta_c \rightarrow K\bar{K}\pi) = (8.5 \pm 1.8)\%$, significantly improving the precision of the world average [11]. Since this branching fraction is used as a reference for all η_c yield measurements, our result will lead to more precise η_c partial widths and more stringent comparisons with theoretical models. For example, from an average of $\mathcal{B}(J/\psi \rightarrow \gamma\eta_c) \times \mathcal{B}(\eta_c \rightarrow K\bar{K}\pi)$ measured by Mark-III [14], DM2 [15], and BES [16], we obtain $\mathcal{B}(J/\psi \rightarrow \gamma\eta_c) = (0.79 \pm 0.20)\%$, and using the value $\Gamma(\eta_c \rightarrow \gamma\gamma) \times \mathcal{B}(\eta_c \rightarrow K\bar{K}\pi) = 0.48 \pm 0.06$ keV [11] we calculate $\Gamma(\eta_c \rightarrow \gamma\gamma) = (5.6 \pm 1.4)$ keV. Both results are more precise than the world average [11]. Similarly, we obtain $\mathcal{B}(\eta_c' \rightarrow K\bar{K}\pi) = (8 \pm 5)\%$ and $\Gamma(\eta_c' \rightarrow \gamma\gamma) = (0.9 \pm 0.5)$ keV.

In conclusion, a novel technique is used to measure directly the absolute branching fractions of the various charmonium states $X_{c\bar{c}}$ in two-body decays $B^{\pm} \rightarrow K^{\pm}X_{c\bar{c}}$ (Table I). The results for $X_{c\bar{c}} = \eta_c, J/\psi, \psi'$ are in agreement with previous measurements, and the η_c result significantly improves the present world average. Upper limits are set for χ_{c0} and χ_{c2}, confirming factorization suppression [17]. Measurements of $B^{\pm} \rightarrow K^{\pm}\eta_c'$ and $B^{\pm} \rightarrow K^{\pm}\psi''$ branching fractions are reported, although with poor significance. Upper limits are given for $X(3872)$ and for production of a possible charged partner in B^0 decays.

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